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Optoelectronic plethysmography: a review of the literature

Pletismografia optoeletrônica: uma revisão da literatura

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Abstract

Background: Optoelectronic plethysmography (OEP) is an innovative method of indirect measurement of pulmonary ventilation, capable of breath-by-breath, three-dimensional, real time assessment of absolute lung volumes and their variations in the three compartments of the chest wall (pulmonary rib cage, abdominal rib cage, and abdomen). OEP allows the measurement of variables of breathing pattern, breathing asynchrony, and contribution of each chest wall compartment and hemithorax to the tidal volume. **Objectives:** To review the literature on the following aspects related to OEP: history, operating principle, advantages, psychometric properties, variables, and method of system analysis, highlighting information about its handling. In a second part, the objective is to analyze the applicability of OEP in different health conditions/situations such as: chronic obstructive pulmonary disease (COPD; acute effects of exercise, pulmonary rehabilitation, breathing exercise, and lung transplantation), asthma, patients in intensive care, neuromuscular diseases, and stroke. **Method:** A search was performed in MedLine, SciELO and Lilacs with the term “optoelectronic plethysmography”. Forty-three papers were included. **Conclusion:** Based on the literature reviewed, OEP has been shown to be an assessment tool that can provide information about ventilatory parameters in healthy subjects and subjects with various dysfunctions in different positions, situations, and settings. The main results of studies on OEP in COPD are shown, representing the largest body of knowledge to date. The results of studies on OEP in other health conditions are also shown.

Keywords: optoelectronic plethysmography; lung volumes; breathing pattern; thoracoabdominal motion; physical therapy; movement.

Resumo

Contextualização: A pletismografia optoeletrônica (POE) é um método inovador de mensuração indireta da ventilação pulmonar, capaz de avaliar ciclo a ciclo, de forma tridimensional e em tempo real, os volumes pulmonares absolutos e suas variações nos três compartimentos que compõem a parede torácica (caixa torácica pulmonar, caixa torácica abdominal e abdome). A POE permite mensurar variáveis do padrão respiratório, da assincronia respiratória, além da contribuição de cada compartimento da parede torácica e de cada hemitórax para o volume corrente. **Objetivos:** Fazer uma revisão de literatura sobre os seguintes aspectos relacionados à POE: histórico, princípio de funcionamento, vantagens de utilização, propriedades psicométricas, variáveis mensuradas e método de análise do sistema, ressaltando informações sobre seu manuseio. Em uma segunda parte, abordar a aplicabilidade da pletismografia optoeletrônica em diferentes condições de saúde/situações, tais como: doença pulmonar obstrutiva crônica (DPOC; efeitos agudos do exercício, reabilitação pulmonar, exercício respiratório e transplante pulmonar), asma, pacientes em terapia intensiva, doenças neuromusculares e hemiplegia. **Método:** Foi realizada uma busca na base de dados MedLine, SciELO e Lilacs com o termo “optoelectronic plethysmography”. Foram incluídos 43 estudos. **Conclusão:** Tendo por base a literatura revisada, a POE mostrou-se um instrumento de avaliação respiratória capaz de fornecer informações sobre parâmetros ventilatórios de indivíduos saudáveis e com disfunções em diferentes posições, situações e ambientes. Foram apresentados os principais resultados dos estudos em que a POE foi usada em indivíduos que apresentavam DPOC, representando o maior corpo de conhecimento até o momento, assim como em alguma outra condição de saúde.

Palavras-chave: pletismografia optoeletrônica; volumes pulmonares; padrão respiratório; movimento toracoabdominal; fisioterapia; movimento.

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Introduction

The assessment of respiratory pattern is part of the treatment provided by physical therapists to individuals with acute or chronic respiratory disorders, in both clinical practice and scientific research. This assessment can be performed in different ways, from visual observation to three-dimensional (3D) analysis of chest wall (CW) and abdomen (AB) movements. The latter is carried out by optoelectronic plethysmography (OEP), an innovative method of indirect measurement of lung ventilation. Thus, the objectives of the present literature review were to show the importance, advantages, variables, and applicability of OEP in different health conditions, such as chronic obstructive pulmonary disease (COPD), asthma, and neuromuscular diseases in different protocols (i.e. rest and exercise), as well as describe the system's method of analysis and provide information on its use.

Definition

The optoelectronic plethysmograph (BTS Bioengineering, Milan, Italy) is an instrument capable of assessing breath-by--breath changes in the total volume of the CW and its different compartments (pulmonary rib cage, abdominal rib cage, and abdomen) based on optical measures of a finite number of displacements of points on the external surface of the CW[1-4]. It is a noninvasive method that does not make any assumptions regarding the number of degrees of freedom of the CW, does not require a mouthpiece, nasal clip or any similar device, and has a relatively simple calibration procedure, without the use of respiratory maneuvers by the subject[1,2].

The main advantages of OEP are that it is a noninvasive and nonionizing method of lung volume measurement capable of detecting small movements of the CW during breathing through the analysis of reflective markers attached to the CW; there is no need to use a mouthpiece, nasal clip or other connector from the equipment to the subject; calibration is fast and without need of subject participation; there are no limitations to the number of degrees of freedom of the CW; the monitoring can happen in different situations and during dynamic evaluations; the volume measures are not influenced by environmental factors (temperature, humidity, and gas composition); it can be combined with pressure, airflow, gas concentration, electrocardiogram, and ultrasound measurements; it is possible to calculate the volumes of three compartments of the CW (pulmonary rib cage, abdominal rib cage, and abdomen); and it allows the analysis of the volumes of the right and left hemithorax separately. Besides, it is possible to estimate the occurrence of dynamic lung hyperinflation, to analyze trunk asymmetries in the sagittal plane, and to evaluate the presence of asynchrony between the three compartments of the CW[1]. OEP can be used in different postures (standing, sitting, supine, and prone)[5-9], conditions (rest, physical exercise, sleep, and mechanical ventilation)[5,6,9-13], and in several dysfunctions (ankylosing spondylitis, COPD, asthma, among others)[14-16].

Background

The measurement of lung ventilation is frequently performed using spirometers or pneumotachometers. However, these measurement tools are associated with different limitations, mainly: a) variations in temperature and humidity, barometric pressure, and viscosity and density of exhaled gases, which can influence measurement; b) devices (mouthpiece, nasal clip or facial mask) to collect breath gases, which can leak; c) additional dead space, which increases tidal volume; d) they cannot be used for evaluation of uncooperative children and adults or during sleep and phonation; e) drift in volume signal from baseline during exercise, which hinders absolute lung volume measurement[1-3].

These limitations have led researchers to look for indirect assessments of respiratory ventilation through external measurements of CW surface movement[17]. In this context, magnetometers and respiratory inductive plethysmography were the instruments most widely used to calculate the dynamic changes in the anterior-posterior and latero-lateral diameters of the CW and of the AB (magnetometers) and in the cross-sectional area of these compartments (respiratory inductive plethysmography)[1-3,18]. However, for these devices, the conversion of one or more dimensions of the chest wall into volume requires calibration coefficients obtained experimentally through special maneuvers by each subject under analysis, combined with spirometric measures. The validity of these coefficients appears to be limited by the body position in which the calibration was performed[1,19].

The operation of these instruments is based on the model of two degrees of freedom of the CW[17], whose limits are frequently exceeded in situations beyond rest condition[2], given that the forces acting on the upper part of the CW, adjacent to the lungs, are very different from those acting on its lower part, adjacent to the diaphragm, and that the AB has at least two areas, one immediately below and with mechanical relationships with CW and another without interactions with CW[20]. Consequently, the measurement of volume change based on the antero-posterior and latero-lateral diameters of the CW and AB or only one cross-sectional area of these compartments seems to be limited and prone to errors[2]. Furthermore, both instruments are incapable of detecting all distortion of the CW and do not have 3D analysis of the behavior of pulmonary volumes[7].

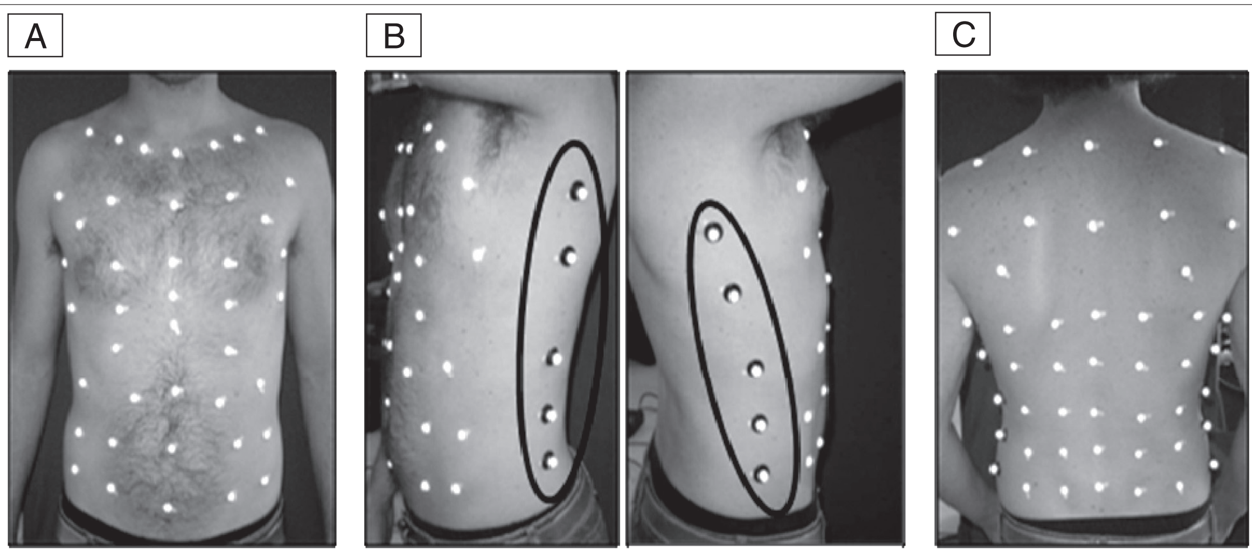
The technological development of image processing and parallel computing allowed the development of optoelectronic motion systems of multiple points positioned on the body's surface[7]. OEP was developed from the ELITE (*Elaboratore di immagini televisive*) motion analysis system, which was the first device to allow 3D motion analysis, having been developed in order to analyze the gait of healthy individuals and of those with disabilities. Thus, it was used in several areas such as in neurophysiology, to better understand basic mechanisms of movement control and related strategies; in orthopedics and motor rehabilitation, for diagnosis and for more detailed and functional evaluation; in neurology, to detect small variations of normality that would not be evident in a simple visual inspection[21]. This equipment was developed in Milan, and reports of its use date back to September 1983. In this system, passive markers were placed on important body points, considering a sampling frequency of 50 Hz[21,22].

In 1994, Ferrigno et al.[21] carried out the first study on the ELITE system to evaluate ventilatory parameters through placement of 32 hemispherical passive markers along vertical and horizontal lines on the individual's CW. The volume is calculated using a geometric model based on 54 tetrahedrons. In this study, the lung volume of twelve healthy individuals was evaluated using the ELITE system and spirometry. However, the authors observed an underestimation of the lung volume obtained by the ELITE system compared with the volume provided by spirometry[7,21]. In order to cover a larger CW area and to correct the errors observed in the study by Ferrigno et al.[21], Cala et al.[7] used 86 markers, and Gorini et al.[23], 89 markers in the measurement of lung volume, finding a more accurate measure of ventilatory parameters compared with the values obtained by spirometry and allowing the anatomical delimitation of three compartments of the chest wall[7,23].

Operation principles

Operation of the OEP is based on an automatic analyzer capable of detecting the movement of passive markers composed of plastic spheres or hemispheres 6 to 10 millimeters in diameter and covered with reflective paper[3,10,24]. In the configuration used for the acquisition in the standing and sitting positions, 89 markers are used (seven horizontal lines, five vertical, two medium-axillary, and seven extra markers) arranged in anatomical structures between the sternal notch and the clavicles to the level of the anterior superior iliac crest, being 37 anterior markers, 42 posterior and ten lateral[1,18,25], as shown in Figure 1. According to this model, the boundary between the pulmonary rib cage and the abdominal rib cage is at the level of the xiphoid appendix and between the abdominal rib cage and the AB, along the costal margin anteriorly and at the lowest point of the costal inferior margin posteriorly[26]. The layout of the 89 markers can be visualized in Figure 1.

According to Aliverti et al.[8] and Romei et al.[27], when the analysis of the ventilatory parameters is performed in the supine or prone positions, 52 markers positioned on the visible part of the chest surface are used.



Source: BTS Bioengineering. Optoelectronic Plethysmography Compedium Marker Setup; A handbook about marker positioning on subjects in standing and supine positions; 2011.

Figure 1. 89 marker setup in the configuration used in the seated and standing positions.

The 3D coordinates of each marker are determined using at least four CCD (charge-coupled device) cameras, which allow the visualization in real time of the scenes to be analyzed[28]. The cameras operate at up to 120 Hz and are synchronized with axial diodes that emit infrared light[2]. The beam of infrared light emitted by the camera flash is reflected by each marker[18] and captured by the cameras. The signal is taken to a dedicated parallel processor, which executes real-time algorithms of pattern recognition to identify the two-dimensional (2D) position (X,Y) of each marker in each camera. After calculating and classifying the 2D coordinates of all markers provided by at least two cameras, the system calculates the 3D coordinates of the different markers by stereophotogrammetry[2,3,29]. In this process, the 3D geometric information is extracted from the combination of, at least, two 2D images obtained by two cameras at a same instant of time and in different positions[28].

The accuracy obtained in the 3D reconstruction is very important because it influences the subsequent processing of data collection, and calibration parameters are necessary in this process[30]. Two calibration procedures are used to determine the 3D coordinates. The first corrects optical distortions[30] and consists of the acquisition of a set of markers placed on a metallic piece in three different axes: X, Y, and Z. The second procedure determines the geometric parameters of the collinearity equations used to calculate the 3D coordinates based on the real coordinates of a set of control points with known location[30]. To achieve this, the researcher moves the Y axis of the metallic piece containing the three reflective markers, "sweeping" the entire collection area where the subject's CW will be positioned.

After obtaining the 3D coordinates of each marker, the volume of the closed surface of the CW is calculated through the connection of points to constitute a net of tetrahedral triangles[1,3]. In this phase, additional virtual points are automatically constructed to facilitate the triangulation in areas where markers cannot be placed[7]. For each triangle, the area and direction of the normal vector are determined. Subsequently, the internal volume of each shape is calculated using Gauss's theorem, in which the surface integral is converted into the volume integral. The total volume of the CW is, then, defined as the sum of the volume of the tetrahedral triangles. Cala et al.[7] and Aliverti and Pedotti[31] provide a detailed description of the application of Gauss's theorem to determine lung volume by the OEP system.

Considering the geometric model of the CW as a whole, it is possible to obtain its variations in volume and the contributions of its different compartments to total lung volume[1], as demonstrated in Figure 2. For this purpose, anatomical boundaries between the different compartments are adopted. It is also possible to calculate the volume of the right and left hemithorax and, therefore, assess asymmetries in respiratory muscle action and CW compliance[2].

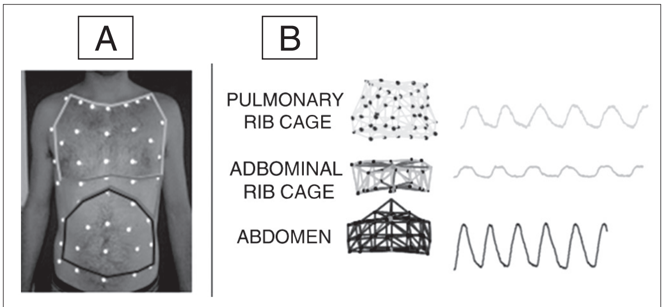
Psychometric properties – validity and reliability

The validity of the OEP to measure volume variations was evaluated in different populations and experimental protocols by comparing tidal volume[5-10,24,32] and inspiratory capacity[6] obtained by means of this instrument with those measured through a spirometer or pneumotachometer. In general, the studies demonstrated good linear relationship between the two methods, with r^2 values above 0.8[6,7,9,10,24,32]. In addition, the difference between the volumes obtained by the different methods was, on average, below 10%[5,6,8-10,24]. The Bland-Altman analysis showed good agreement among the methods[8,9,24].

Although the validity of the OEP has been analyzed in different studies, the reliability of this instrument was evaluated in only two studies[33,34], neither of which had as primary goal the evaluation of the instrument's reliability. In both studies, a reduced number of individuals was evaluated, details on the experimental protocols were not provided, and the complete statistical analysis recommended to evaluate reliability was not used or described. Recently, in our laboratory, the reliability of OEP was evaluated in 32 healthy individuals at rest and during exercise on a cycle ergometer. The system showed good intra – and inter-rater reliability, with Intraclass Correlation Coefficients above 0.75 for most of the analyzed variables[35].

Variables measured

Through OEP, in each respiratory cycle, volume and time variables of the three CW compartments and of both



Source: BTS Bioengineering. Optoelectronic Plethysmography Compedium Marker Setup; A handbook about marker positioning on subjects in standing and supine positions; 2011.

Figure 2. Representation of the three compartments of the chest wall. A – limits of the three compartments of the chest wall in an anterior view. B – geometric models and respective tracings related to the volume generated in each of the three compartments.

hemithoraxes are measured breath-by-breath, as well as variables that reflect the thoracoabdominal asynchrony[1,18,33,36].

Volume variables

It is possible to measure the tidal volume of the CW and of its three compartments, as well as calculate the end--inspiratory and expiratory volumes, that is, the total volume found at the end of one inspiration and expiration, respectively. Absolute volumes (in liters) of the CW, of its three compartments, and of each hemithorax are calculated as the difference between the end-inspiratory volume and the end--expiratory volume of the same compartment[10,18,34]. Different volume variables, measured in liters, can be assessed through OEP: tidal volume of CW (V_{cw}), tidal volume of pulmonary rib cage (V_{rcp}), tidal volume of abdominal rib cage (V_{rca}), tidal volume of AB (V_{ab}), CW end-expiratory volume (Vee_{cw}), rib cage end-expiratory volume (Vee_{rc}), abdominal rib cage end--expiratory volume (Vee_{rca}), AB end-expiratory volume (Vee_{ab}), CW end-inspiratory volume (Vei_{cw}), rib cage end-inspiratory volume (Vei_{rc}), abdominal rib cage end-inspiratory volume (Vei_{rca}), and AB end – inspiration volume (Vei_{ab}).

The relative volumes are calculated as percentage (%) of contribution of each compartment to the CW tidal volume: percentage contribution of pulmonary rib cage ($V_{rcp\%}$), percentage contribution of abdominal rib cage ($V_{rca\%}$), and percentage contribution of AB ($V_{ab\%}$). If maximal inspirations are performed repeatedly during the exercise, changes in CW volume can also be calculated regarding the total lung capacity (TLC), and it is possible to determine restriction in tidal volume when the end-inspiratory volume is close to TLC[6].

Time variables

In each respiratory cycle, it is possible to determine the total time of the respiratory cycle, the inspiration and expiratory time, and the ratio between inspiratory time and total time of the cycle. The inspiratory and expiratory flows, respiratory rate (RR), and minute ventilation (product of respiratory rate and tidal volume) are also calculated. The time variables measured in seconds through OEP are: inspiratory time (Ti), expiratory time (Te), and total time of the respiratory cycle (Ttot). Besides these, the following variables can be calculated: inspiratory time in relation to the total time (Ti/Ttot), RR in breathing incursions per minute, minute ventilation (VE) in liters per minute, and mean inspiratory flow (VCcw/ti) and mean expiratory flow (VCcw/te) in liters per second.

Thoracoabdominal asynchrony variables

Asynchrony is defined as the difference in time of expansion or retraction between the compartments of the CW. When this difference is so great that the movement among the compartments becomes opposite, paradoxical movement occurs[19,37]. Using signal processing software, such as MATLAB®, it is possible to obtain variables that are used to evaluate thoracoabdominal movement. Among them, the following variables stand out: phase angle (PhAng), inspiratory phase ratio (PhRIB), expiratory phase ratio (PhREB), total phase ratio (PhRTB), and the cross-correlation function (CCF). These variables are especially used for the analysis of thoracoabdominal asynchrony.

The PhAng reflects the delay between excursions of two compartments of the CW, as described previously. It is measured in degrees (º), ranging from 0º to 180º, where 0º represents perfect synchrony, while 180º represent paradoxical movement. The PhAng calculation is frequently performed through equations extracted from the Konno-Mead loop, or Lissajous figure, in which movements of one compartment during one respiratory cycle are plotted against the excursion of a second compartment in an X-Y graph[19,37-40]. According to the method proposed by Agostoni and Mognoni[82], for PhAng lower than 90º, the calculation is made using the following formula: sen$\Phi = m/s$; and for PhAng between 90º and 180º: $\Phi = 180 - \mu$, where $\mu = m/s$. The parameter "m" represents the width of the figure at the midpoint of the maximal excursion of the compartment represented in the Y axis, and "s", the maximal excursion of the compartment shown in the X axis[38].

The PhAng quantification has the advantage of incorporating data gathered throughout the respiratory cycle. However, its calculation assumes that the movement of the rib cage (RC) and AB has an almost sinusoidal shape, which may not represent the reality of the measure[41]. Therefore, it is recommended that non-sinusoidal curves and/or figure-eight curves should be discarded from analysis as they may affect the measurement of PhAng[41]. For curves with PhAng greater than 20°, the direction of the curve may be identified and used to verify which compartment begins the respiratory cycle. A clockwise curve indicates that the RC precedes the AB, and a counterclockwise curve, that the AB precedes the CW[38].

The PhRIB/ PhREB ratio expresses the percentage of time of the respiratory cycle in which the compartments of the RC and AB move in different directions. Thus, 0% represents perfect synchrony, while 100% indicates paradoxical movement. The advantage of these variables is that they quantify the asynchrony at each point of the respiratory cycle and do not require sinusoidal curves or calculations derived from the Konno-Mead loop[40].

The CCF determines the delay in seconds among the compartments. Therefore, the perfect thoracoabdominal synchrony represents 0 second of delay. The higher the CCF, the greater the asynchrony between the compartments of the CW[42]. More recently, Aliverti et al.[33] used, in addition to the PhAng, the variable paradoxical inspiratory time (PI) in order to evaluate the asynchrony of the CW compartments in patients with COPD during exercise on a cycle ergometer. This variable was defined as the fraction of inspiratory time, in percentage, in which the volume of abdominal rib cage decreases.

Applicability of optoeletronic plethysmography

OEP allows the analysis of CW volumes in healthy individuals or in those with disorders in several circumstances: during physical exercise[5,6,43]; during mechanical ventilation monitoring in order to verify, for instance, the effects of end-expiratory pressure[l9,12]; during sleep to assess apnea and the effects of positive pressure on the airways; during speech[46], laughter[47], and coughing[48,49]; during exercise with inspiratory threshold[13]; for monitoring during anesthesia procedures; for analysis of pulmonary hyperinflation[15,44]; to evaluate individuals with neurological disorders, such as hemiplegia[45]; to evaluate individuals with ankylosing spondylitis[14]; to evaluate the effects of postures on the respiratory pattern[27] and on the impedance of the respiratory system[11,50].

In 1997, Aliverti et al.[51] and Kenyon et al.[32] validated protocols for the use of OEP in healthy individuals during baseline breathing and exercise on the cycle ergometer. Later, protocols were created for the prone and supine positions in patients in intensive care[8,9]. The kinematic changes in the CW have also been assessed during upper limb exercise compared to lower limb exercise in healthy individuals[26].

Regarding the employment of the instrument for analysis of individuals with different respiratory diseases, Filippelli et al.[15] evaluated the volume changes of the CW in response to bronchoconstriction in individuals with asthma[15]; however the great majority of studies included individuals with COPD. These individuals were assessed through OEP at rest and during exercise, as well as during specific respiratory maneuvers such as the use of pursed--lip expiration[6,16,25,34].

Analysis of variation of end-expiratory lung volume is frequently used to verify the occurrence of dynamic lung hyperinflation (DH) in patients with airflow limitation (asthmatic and/or with COPD) during the performance of maximal and/or submaximal tests on the cycle ergometer or electromagnetic treadmill[6,15]. Analysis of inspiratory capacity by the OEP is calculated as the difference between the TLC of the CW and its end-expiratory volume, and the mean of the end-expiratory volume of the 20 seconds prior to the measurement of inspiratory capacity is usually chosen[5]. The evaluation of this maneuver through this instrument has already been validated in comparison with dynamic spirometry, which is considered the gold standard[5].

When OEP is combined with measures of gastric and esophageal pressure, it is possible to measure the pressure and work of the breathing muscles. It is also possible to measure the blood displacement from the trunk to the extremities[52] based on the combination with esophageal pressure or with whole-body plethysmography[1].

According to Aliverti and Pedotti[31], one of the most important characteristics of OEP is that the subdivision of CW volumes does not suppose degrees of freedom[1]. Thus, the capacity of the instrument to measure subdivisions between the expansion of the right and left hemithorax can be useful when there are asymmetries in respiratory muscle action and changes in lung compliance, such as in patients with hemiplegia or ankylosing spondylitis[14,45]. It should be noted that the relationship between asymmetry of lung ventilation and expansion of the CW is still questionable and needs further study.

Unlike spirometry, OEP measures the total volume of the CW[53]. Therefore, when the respiratory system undergoes high variations in pressure, such as during mechanical ventilation or during exercise in patients with airflow limitation, the change in CW total volume may also include changes in the blood volume of the thorax and AB[1]. In these cases, the instrument allows the difference between the measures of CW volume and exhaled volume during baseline breathing to be used to calculate the volume of compressed gas and the volume of change in blood flow from thorax to extremities, when combined with whole-body plethysmography[1,52,53].

Main results shown in the literature

In September 2011, a search in MedLine, SciELO, and Lilacs databases with the term "optoelectronic plethysmography" was performed and 56 studies were found. After reading the title and abstracts, those which referred to OEP were included, totalizing 43 papers. After reading the full texts of these studies, 25 more studies were found by manual search. Thus, a total of 68 studies on OEP was selected.

Table 1 lists the authors who carried out studies on validation of the technique, as well as those performed with healthy individuals with the respective references. Table 2 shows the objectives, the characteristics of the studied sample and the main results observed in the studies that evaluated patients with COPD. Table 3 shows data from studies performed in patients with other health conditions.

Table 1. Studies on validation of optoelectronic plethysmography and evaluation of healthy subjects.

Literature review and validation studies	
Ferrigno and Pedotti[22]; Ward et al.[20]; Ferrigno 1994[21]; Calla et al.[7]; Iandelli et al.[54]; Aliverti and Pedotti[1]; Macklem[53]; Skoczylas et al.[55]; Aliverti[2]; Romagnoli[18]; Dellacà et al.[24]; Capelli et al.[56]; Layton et al.[57]	
Healthy Subjects	
Walking	Duranti et al.[58]
Diaphragmatic function	Aliverti et al.[59]; Aliverti et al.[60]
Blood shift	Aliverti et al.[52]
Exercise	Aliverti et al.[51]; Kenyon et al.[32]; Aliverti et al.[3]; Aliverti et al.[61]; Iandelli et al.[4]; Aliverti et al.[62]; Vogiatzis et al.[5]; Romagnoli et al.[26]; Vogiatzis et al.[63]; Wüst et al.[43]
Phonation	Binazzi et al.[46]
Hypercapnia	Romagnoli et al.[64]; Illi et al.[65]
Respiratory system impedance	Aliverti et al.[11]; Dellacà et al.[50]
Posture	Aliverti et al.[8]; Dellacà et al.[66]; Wang et al.[67]; Romei et al.[27]
Laughing	Filippelli et al.[47]
Respiratory muscle overload	Hostettler et al.[13]
Coughing	Lanini et al.[48]

Table 2. Studies evaluating patients with Chronic Obstructive Pulmonary Disease.

Authors and aims	Sample characteristics	Main results
Physical exercise		
Aliverti et al.[10] To assess how the chest wall volumes changed as dynamic hyperinflation developed in patients with clinically stable symptomatic COPD.	n=20; Age: 68.6±7 years; BMI: 25.5±2.8 kg/m^2; $FEV_{1:}$ 43.6±11.6 %pred; FRC: 174.2±44.1 %pred; TLC: 128.7±18.7 %pred; RV: 202.9±59.6 %pred	During exercise: Chest wall: Vee_{cw} increased in patients who developed dynamic hyperinflation (hyperinflators, n=8) and reduced in patients without hyperinflation (euvolumics, n=12) • Euvolumics: V_{cw} increased by reducing the Vee_{ab}, exercised for less time and reached a lower peak workload during the incremental exercise test • Hyperinflated: V_{cw} increased by increasing the Vei_{ab} and Vei_{cw}
Aliverti et al.[68] To evaluate the action of salbutamol on the chest wall volumes at rest and during exercise in patients with clinically stable symptomatic COPD.	n=18; Age: 67.1±6.3 years; BMI: 24.3±4.2 kg/m^2; $FEV_{1:}$ 40.6±15 %pred; FRC: 175.8±26 %pred; TLC: 125.7±11. 6 %pred; RV: 215.6±47.1 %pred	• Increase: FEV_1, FVC and inspiratory capacity • Reduction: FRC and RV • OEP showed changes in FRC at rest especially in the abdominal compartment after the use of salbutamol • Vee_{cw}lower in the end of the exercise, but the exercise time was not changed after the use of salbutamol
Vogiatzis et al.[6] To identify the pattern of change in chest wall volumes during exercise and during its recovery in patients with severe COPD.	n=20; Age: 62±2 years; BMI: 23.7±0.7 kg/m^2; $FEV_{1:}$ 35±2 %pred; FRC: 156±14 %pred; TLC: 120±22 %pred; RV: 216±10 %pred	During exercise both groups reached similar peak workload • Earlyhyperinflators(n=12): Vee_{cw}increased-progressivelyduring exercise, reaching 750±90 ml at peak workload. Vee_{cw} remained 254±130ml above baseline 3 minutes after exercise only in this group • Later hyperinflators (n=8): Vee_{cw}unchanged up to 66% of the peak workload and an increase of 210±80 ml at peak exercise
Vogiatzis et al.[69] To investigate how Vee_{rc} and Vee_{ab} regulation during exercise is related to the degree of dynamic chest wall hyperinflation in patients with different spirometric severity of COPD based on the GOLD classification.	GOLD II (n=14): Age: 67±7 years; BMI: 77±34 kg/m^2; FEV_1: 61±8 %pred; FEV_1/FVC= 51±6; FRC: 3.17±0.69 Liters GOLD III (n=14): Age: 64±8 years; BMI: 24.8±3.15 kg/m^2; FEV_1:42±4 %pred; FEV_1/FVC= 44±10; FRC: 2.63±0.72 Liters GOLD IV (n=14): Age: 58±7 years; BMI: 23.8±2.46 kg/m^2; $FEV_{1:}$ 24±3 %pred; FEV_1/FVC= 28±5 FRC: 2.61±0.74 Liters	• GOLD II: had significantly lower Vee_{ab} during exercise as well as the healthy control group • GOLD III and IV: atpeak workload, only these patients exhibited a statistically significant increase ofVee_{cw}. There were no reductions inVee_{ab}

Table 2. Continue.

Physical exercise		
Romagnoli et al.[70] To evaluate the influence of unsupported upper limb exercise in patients with COPD.	n=13; Age: 69.5±7.7 years; BMI: 24.9±4.5 kg/m^2; FEV$_1$:45.1±13.8 %pred; FEV$_1$/FVC= 47.5±13; FRC: 4.9±1.2 Liters	• During upper limb exercise without support, dynamic hyperinflation was not observed • In some subjects there was paradoxical movement of pulmonary chest wall and in others of the abdominal chest wall • Chest wall movement was proportional to the increase in ventilation
Pulmonary Rehabilitation		
Georgiadou et al.[34] To investigate the effect of pulmonary rehabilitation on chest wall volumes and its compartments during exercise in patients with COPD.	Early hyperinflators (n=11): Age: 60±2 years; BMI: 23.7±0.6 kg/m^2; FEV$_1$: 32±3 %pred; FEV$_1$/FVC= 37±3; FRC:5.85±0.31Liters Later hyperinflators (n=9): Age: 67±3 years; BMI: 27.2±1.1 kg/m^2; FEV$_1$:48±4 %pred; FEV$_1$/FVC= 43±3; FRC: 5.21±0.32 Liters	• After rehabilitation, the peak workload increased significantly in early and in later hyperinflators • After rehabilitation, at a same workload, there was a reduction in VE, *f*, Vee$_{cw}$ and Vei$_{cw}$
Respiratory Exercise		
Bianchi et al.[16] To define the effect of pursed-lip breathing on chest wall compartmental volumes.	n=22 (11 with pulmonary hyperinflation – FRC: 141-212 %pred) COPD: moderate to severe; Age: 71±7 years; Height: 171±8 cm; Weight: 76±10 Kg VC: 84±19%pred; FEV$_1$: 43±16%pred; FRC: 134±37%pred; TLC: 109±37%pred; RV: 151±52%pred; MRC: 3.0±0.8	During pursed-lip breathing: • Increase: V$_{cw}$, Ti, Te, Ttot, V$_{cw}$/ti, Vei$_{cw}$ and Vei$_{rc}$ • Reduction: *f*, Ti/Ttot, Vee$_{cw}$, Vee$_{rc}$, Vee$_{ab}$ • Vee$_{cw}$: primarily responsible for the variance in Borg scale
Bianchi et al.[25] To evaluate whether changes in chest wall volumes can help to identify the reason why not all patients benefit from the pursed-lip breathing.	n=30; Age: 71±7 years; BMI: 26±3 kg/m^2; VC: 87±21 %pred; FEV$_1$: 45±16 %pred; FEV$_1$/FVC: 38±11%; FRC: 138±38 %pred; TLC: 111±20 %pred; RV: 156±56 Liters; MRC: 2.9±0.8	• Euvolumics (n=11): reduced Vee$_{cw}$ and Vee$_{ab}$ associated with an increase of Vei$_{cw}$ and Vei$_{rc}$ during pursed lips • Hyperinflated (n=19): increased Vee$_{cw}$, Vee$_{rc}$, Vei$_{cw}$, Vei$_{rc}$ and Vei$_{ab}$ during pursed lips
Paradoxal Movement and Exercise		
Aliverti et al.[33] To evaluate whether the presence of paradoxical movement of the abdominal rib cage may be related to changes in chest wall volumes during exercise.	COPD (n=20) Age: 66±7 years; BMI: 22.5±3.9 kg/m^2; FEV$_1$: 32.6±11.7 %pred; FEV$_1$/FVC= 36.3±9.4; FVC: 2.9±0.78 Liters Control (n=10) Age: 65±7 years; BMI: 25.6±6 kg/m^2; FEV$_1$:102.8±12.7 %pred; FEV$_1$/FVC= 67±11.6; FVC: 5±1.29 Liters	• 8 patients had paradoxical motion at rest (P +) and 12 did not (P-). This result was not related to lung function or exercise tolerance • Vee$_{cw}$ increased immediately at the beginning of the exercise in P +, but later in the P – • Dyspnoea increased similarly in both groups
Hoover's Sign		
Binazzi et al.[36] To verify whether lung hyperinflation can lead to rib cage distortion.	Patients with Hoover's Sign (n=9) Age: 69±8 years; BMI: 27±3 kg/m^2; VC:79±24 %pred; FEV$_1$:32±11 %pred; FEV$_1$/FVC: 31±8; FRC:175±28 %pred; TLC:126±20 %pred; Patients without Hoover's Sign (n=11) Age: 71±4 years; BMI:24±4 kg/m^2; CV:91±17%pred; FEV$_1$:43±10%pred; FEV$_1$/FVC 36±10; FRC:136±41 Liters; TLC:112±17 Liters Control (n=8) Age: 60±10 years; BMI: 24±2.5 kg/m^2; CV:100±8 %pred; FEV$_1$:96±7 %pred; FEV$_1$/FVC: 81±6; FRC:103±17 %pred; TLC:101±10 %pred	• V$_{rcp}$, V$_{rca}$and percentage contribution of abdominal compartment to V$_{cw}$ were similar in patients with and without Hoover's sign • V$_{cw}$, V$_{rcp}$, V$_{rca}$, V$_{rcp}$/V$_{rca}$ and V$_{ab}$: were able to quantify Hoover's sign, but did not correlate with the degree of lung hyperinflation • V$_{cw}$ and V$_{ab}$ were higher in patients with Hoover's sign than in control group • V$_{rc}$ and V$_{rcp}$ were lower in subjects with Hoover's sign than in the control group

Table 2. Continue.

Lung Transplantation		
De Groote et al.[71] To assess whether the expansion of the chest wall and asymmetrical shift of the mediastinum are involved in asymmetric ventilation after lung transplantation due to emphysema.	Patients undergoing lung transplantation due to emphysema (n=4) Age: 59±1.87 years; Height: 175±5.70 cm; Weight: 66.75±9.96 Kg; FEV_1: 53.25±4.26 %pred	• Volume of both hemithorax: similar at FRC and TLC • Changes in volume during forced expiratory maneuver and hyperpnea: not indicated differences between the native and transplanted lung • Very low PhAng values were observed
Khirani et al.[72] To investigate whether the online monitoring of lung mechanics, including intrinsic PEEP, it would be possible in patients with spontaneous ventilation pre-lung transplant.	Patients with COPD (n=9): Age: 57.9±7.9 years; FEV_1: 23±9 %pred; FRC:139±43 %pred; TLC: 101±23%pred Patients with cystic fibrosis (n=11): Age: 28.4±6.6 years; FEV_1: 26±6 % pred; FRC: 81±38 %pred; TLC: 66±19 %pred	• In patients with COPD, the mean values of dynamic pulmonary elastance and inspiratory resistance were different between the two monitoring methods (minimally modified square of intrinsic PEEP and methods of multiple linear regression of intrinsic PEEP), and in patients with cystic fibrosis there was no difference • The correlations between measures of the two monitoring methods were of high magnitude for all comparisons • According to the Bland-Altman analysis, the differences were small and confidence intervals acceptable
Wilkens et al.[73] To test the hypothesis that the different characteristics of pulmonary fibrosis, cystic fibrosis and COPD would lead to different breathing patterns at rest and during exercise and the adaptations of chronic ventilatory pattern were reversible after lung transplantation.	Patients with pulmonary fibrosis (n=9): Age: 53.89±4.19 years; FEV_1:37.88±3.56 %pred; FVC: 31.71±2.55 Liters; TLC: 45.84±3.96 Liters Patients with cystic fibrosis (n=9): Age: 32.89±3.05 years; FEV_1: 22.46±2.81 %pred; FVC: 29.73±3.34 Liters; TLC: 96.19±7.63 Liters Patients with COPD: (n=21) Age: 54.43±1.02 years; FEV_1:20.77±1.15 %pred; FVC: 45.66±2.50 Liters; TLC: 149.54±6.28 Liters Healthy patients (n=10): Age: 52.20±2.62 years; FEV_1: 102.69±3.35 %pred; FVC: 101.80±3.74 Liters; TLC:105.96±4.27 Liters TP patients after lung transplantation (n=16) Age: 51.13±2.42 years; FEV_1:79.40±6.46 %pred; FVC: 79.73±5.85 Liters; TLC: 87.33±5.92 Liters	Three different breathing patterns were found at FRC level in the groups • Patients with COPD: Ti/Ttot was reduced at rest and at peak exercise, increased Vee_{cw} andVee_{rc} during exercise • Patients with pulmonary fibrosis: at maximal exercise *f* increased without change in V_{cw}, Vei_{rc} andVei_{cw} not changed • Patients with cystic fibrosis: at maximal exercise, *f*, tidal volume, Vei_{rc}, Vei_{cw} increased • Patients after lung transplantation: breathing pattern was similar to that of healthy patients
Inspiratory Capacity		
Duranti et al.[74] To validate the measurement of inspiratory capacity by the OEP system.	n=13 Age: 66±7 years; Height: 173±6 cm; BMI: 28.6±3.4 kg/m^2; FEV_1:45±21 %pred; FVC: 71±22 %pred; FRC: 142±32%pred; RV:172±48%pred; TLC: 113±10%pred	*After Albulterol:* • Increase: FEV_1 and FVC • There was no change of V_{cw} at TLC level and in the breathing patterns • Reduction: V_{cw} at FRC level which did not correlate with spirometric variables or with the breathing pattern • Inspiratory capacity measured by the pneumotachograph was strongly correlated with inspiratory capacity measures by OEP measured and showed no differences between devices

% pred: % predicted value; BMI: Body Mass Index; COPD: Chronic Obstructive Pulmonary Disease; *f* (min^{-1}): respiratory frequency; FEV_1: Forced expiratory volume in the first second; FRC: Functional Residual Capacity; FVC: Forced Vital Capacity; GOLD: Global Initiative for Chronic Obstructive Lung Disease; MRC: Medical Research Council dyspnoea scale; OEP: optoelectronic plethysmography; PEEP: Positive end expiratory pressure; PhAng: Phase angle; RV: Residual Volume; Te (s): Expiratory time; Ti (s): inspiratory time; TLC: Total Lung Capacity; Ttot (s): total time of the respiratory cycle; VC: Vital Capacity; VE: minute ventilation; Vee_{ab}(L): abdomen end-expiratory volume; Vee_{cw}(L): chest wall end-expiratory volume; Vee_{rc} (L): rib cage end-expiratory volume; Vei_{ab}(L): abdomen end-inspiratory volume; Vei_{cw}(L): chest wall end-inspiratory volume; Vei_{rc} (L): rib cage end-inspiratory volume; V_{ab}(L): abdominal volume; V_{cw} (L): chest wall volume; V_{cw}/ti (L/s): inspiratory flow; V_{rc} (L): rib cage volume; V_{rca}(L): abdominal rib cage volume; V_{rcp}(L): pulmonary rib cage volume.

Table 3. Studies evaluating patients with other health conditions.

Authors and aims	Sample characteristics	Main results
Asthma		
Gorini et al.[23] To verify whether the ELITE system is able to estimate lung volume during acute bronchoconstriction and during quiet breathing at rest; to assess the degree of hyperinflation associated with acute bronchoconstriction and its partitioning into chest wall compartments; to assess the relationships between hyperinflation and respiratory muscle recruitment and interaction.	n=7; Age: 40.1±4.2 years; FEV_1:88±4.1 %pred; FRC: 93.8±5.4 %pred; TLC: 97.6±3 %pred	During bronchoconstriction: Hyperinflation occurred due to the increase in Vee_{rc}, and changes in V_{ab} were shown to be inconsistent • Changes in pulmonary rib cage and abdominal rib cage end-expiratory volumes occurred during relaxation, indicating that these compartments divided hyperinflation • Changes in Vee_{cw} were not related to changes in FEV_1, in time nor in the volumes of the compartments during the respiratory cycle
Filippelli et al.[15] To evaluate the contribution of increased V_{cw} and its components in the sensation of dyspnea in asthmatics after using methacholine.	n=8; Age: 34±12 years; Weight: 74±11.4 Kg; Height: 177±0.12 cm; VC: 5.56±0.91 %pred; FRC: 3.66±0.66 %pred; FEV_1: 4.24±0.67 Liters; FEV_1/FVC: 78±8%	After methacholine: • Reduction: FEV_1 • Increase: Borg scale score, Vee_{cw}, Vee_{rc}, Vee_{ab}, and the Vee_{cw} increase (hyperinflation) was primarily responsible for higher scores in
Intensive care – Lobectomy		
Bastianini, et al.[75] To test OEP as a system to assess the efficacy of respiratory rehabilitation in the presence of asymmetric ventilation.	Patients who underwent right or left upper lobectomy (n=14): 10 women and 4 men	• Differences in tidal volume of the chest wall were observed between paretic and healthy sides • Significant tidal volume increase has been observed for non-operated side between pre-surgery and post-rehabilitation phases during quiet breathing, • There were no differences in V_{cw} between the three phases (pre-surgery, post-surgery and post-rehabilitation)
Intensive care – Positive End-Expiratory Pressure (PEEP)		
Dellacà et al.[44] To test the ability of OEP to monitor changes induced by PEEP in lung volumes of mechanically ventilated patients.	n=8; Age: 58.4±13 years; Oxygen Blood Pressure: 113.6±20.0 Torr; ; Fraction of Inspired Oxygen: 43.1±9.2 %; PEEP: 10.2±5.9 cmH_2O	• The volume measurements showed variations of up to 16±4 ml • The regression line between changes in end-expiratory chest wall volume measured by helium and Vee_{cw} measured by OEP were shown to be very close to the identity line • After increasing PEEP, the new equilibrium state of the end-expiratory volume of the chest wall was achieved in about 15 breaths, after PEEP • decrease, in 3–4 breaths • The slow increase in Vee_{cw} was mainly because of the abdominal compartment
Intensive care – Acute Respiratory Distress Syndrome		
Aliverti et al.[9] To evaluate the feasibility of using OEP in patients admitted to an Intensive Care Unit and report preliminary results regarding the distribution of chest wall volume.	Patients using pressure support ventilation (n=7): Age: 62,6.±7.5 years Patients using continuous positive pressure ventilation (n=6): Age: 66.5±14.1 years Healthy subjects (n=11): Age: 28.0±4.5 years	• The measurements generated by spirometry, pneumotachography and OEP showed high magnitude correlations • The abdominal contribution to inspired volume was higher in healthy subjects than in patients with acute respiratory distress syndrome and COPD during pressure support ventilation • No differences were found between the pressure support of 5 and 25 cmH_2O between groups

Table 3. Continue.

Intensive care – Acute Respiratory Distress Syndrome		
Chiumello et al.[76] To quantify volume changes and to investigate the mechanisms of pressure-volume curve in patients with acute lung injury and acute respiratory distress syndrome.	n=10; Age: 70±13 years; Ratio between Oxygen Blood Pressure and Fraction of Inspired Oxygen: 222±67; PEEP: 11.2±4.4 cmH_2O	• Starting compliance inflation/deflation compliance, hysteresis and unrecovered volume were affected by volume shift • The volume shift was directly related to the product time of inflation, to esophageal pressure/ airway pressure and central venous pressure • There was a negative correlation between the shift in volume and time of deflation of pressure-volume curve
Intensive care – Mechanical Ventilation		
Aliverti et al.[12] To analyze the effects of different parameters of pressure support in ventilation pattern, kinematics of the chest wall and its compartments and the work of breathing in patients with acute lung injury.	n=9; Age: 59.3±13.2 years; ratio between oxygen blood pressure and fraction of inspired oxygen: 277.6±78.3 mmHg; fraction of inspired oxygen: 0.37 ± 0.1%; PEEP: 6.9±4.6 cmH_2O	• Constant minute ventilation with large variations in the ratio of respiratory rate/tidal volume at all levels of pressure support • In support pressure below 15 cmH_2O it were observed increases in the pressure developed by inspiratory and expiratory muscles, the rib cage contribution to tidal volume, the phase angle between the rib cage and abdomen
Neuromuscular disease – Spinal Muscular Atrophy		
Lissoni et al.[77] To analyze the kinematics of the chest wall in spontaneously breathing and in deep breathing.	Patients with spinal muscular atrophy type 2 (n=12): Age: 10.5±4.25 years; VC: 33.8±19.9 Liters Healthy children (n=13) Age: 6.8±2.5 years	• In patients, the abdomen contributed about 96% during quiet breathing and 87% in deep breathing while in the control group the contribution was 74% and 41%, respectively • The contribution of pulmonary rib cage was – 1.7% in quiet breathing and at 0.3% in deep breathing in patients
Lissoni et al.[78] To determine the effect of assisted ventilation (non-invasive), in the compartments of the chest wall in patients with spinal muscular atrophy type 2.	Patients with type 2 spinal muscular atrophy (n=9): Age: 6.8±3.7 years; VC: 560±289 ml; VC: 21.33±10.19 %pred; Maximal Inspiratory Pressure: – 27.67±13.14 cmH_2O – they were studied during spontaneous breathing and assisted ventilation Healthy children (n=13): Age: 6.9±2.5 years; were studied only during spontaneous breathing	• The kinematic demonstrated a paradoxical breathing pattern in patients with spinal muscular atrophy type 2 during spontaneously breathing • During assisted ventilation, the volume contribution of each compartment of the chest wall was equivalent to that observed during spontaneous breathing in healthy children
Neuromuscular disease – Muscular Dystrophies		
D'Angelo et al.[79] To study the function of the chest wall in patients with progressive muscular dystrophy. To measure the thoracoabdominal movement and characterize the kinematics of the chest wall, reflecting respiratory muscle action.	Limb Girdle Muscular Dystrophy, (n=38): Age: 37.6±12.5 years; FEV_1: 77.9±23.0 %pred; FRC: 77.1±24 Liters; TLC: 83.3±20.9 Liters; FRC: 89.0±24.6 Liters Becker Muscular Dystrophy (n=20): Age: 32.7±12.2 years; FEV_1:97.2±18.4 %pred; FRC: 94.6±16.3 Liters; TLC: 99.9±14.2 Liters; FRC: 107.7±18.8 Liters Facio-Scapulo-Humeral Dystrophy (n=30): Age: 43.7±17.5 years; FEV_1:81.3±20.9 %pred; FRC: 82.6±20.9 Liters; TLC: 85.9±14.8 Liters; FRC: 86.2±24.2 Liters Healthy subjects (n=20): Age: 32.7±9.3 years	• Patients with restrictive syndrome (Limb Girdle Muscular Dystrophy and Facio-Scapulo-Humeral Dystrophy) in the later stages of the disease showed different thoracoabdominal patterns compared to healthy subjects in a sitting position and during maneuvers such as slow vital capacity • The involvement of respiratory muscles was more pronounced in groups with Limb Girdle Muscular Dystrophy and Facio-Scapulo-Humeral Dystrophy than in the Becker Muscular Dystrophy group • There was a smaller abdomen contribution in patients who used wheelchair
Neuromuscular disease – Duchene muscular dystrophy		
Lo Mauro et al.[80] To determine whether a detailed analysis of chest wall could identify new parameters associated with aspects of disease progression.	Patients with Duchenne muscular dystrophy (n=66): Age: 12.64±0.63 years; FEV_1:56.67±3.32 % pred; FRC: 53.30±2.81 Liters; TLC: 68.98±2.71 Liters; FRC: 81.21±3.70 Liters Control Group (n=21): Age: 13.5±1.4 years	• In the seated position, no differences were found between patients and control group and between groups of different ages • In the supine position, the average contribution of V_{ab} for the tidal volume decreased progressively with age • Patients with nocturnal hypoxemia demonstrated lower abdominal contribution to tidal volume

Table 3. Continue.

Neuromuscular disease – Cough		
Lanini et al.[49] To evaluate the hypothesis that forces generated in the chest wall influence the distribution of volumes in its compartments, resulting in distortion of the chest wall and reduce the cough effectiveness.	Patients (n=8): Age: 55.4±8.6 years; FEV_1: 68.3±22.6 %pred; FRC: 80.6±9.8 Liters; TLC: 73.3±14.0 Liters Healthy subjects (n=12): Age: 49.2±6.5 years; FEV_1:100.9±11.6 %pred; FRC: 111.9±22.8 Liters; TLC: 102.9±13.6 Liters	• Only patients showed no reduction in Vee_{cw}, besides presenting greater distortion of the chest wall during cough • The cough peak flow was negatively correlated with the distortion of the chest wall, but not with respiratory muscle strength
Hemiplegic		
Lanini et al.[45] To evaluate the differences in volume between chest wall hemicompartments during quiet breathing, voluntary hyperventilation and hypercapnic stimulation in patients with hemiparesis due to stroke.	Hemiplegics Patients (n=8): Age: 54.9±13.5 years; FEV_1: 91.5±18.1 %pred; FRC: 90.8±12.0 Liters; TLC: 92.0±14.2 Liters; FRC: 99.3±17.3 Liters Healthy patients (n=9): Age: 51.9±10.2 years; FEV_1: 102.3±11.2 %pred; FRC: 98.5±13.2 Liters; TLC: 97.2±15.0 Liters; FRC: 100.2±16.2 Liters	Hemiplegic Patients: • Volumes of paretic hemicompartment and non-paretic were similar during quiet breathing • Volume of paretic hemicompartment was lower during voluntary hyperventilation in six patients and increased during hypercapnic stimulation in all healthy group • There was no asymmetry in the evaluated condition
Ankylosing spondylitis		
Romagnoli et al.[14] To validate the hypothesis that in patients with ankylosing spondylitis and limited expansion of the chest wall, a central strategy to help the diaphragm should involve the coordinated action of this muscle with the abdominal muscles.	Ankylosing spondylitis patients (n=6): Age: 46.0±15.2 years; FEV_1: 92.7±15.3 %pred; VC: 89.7±17.7 Liters; TLC: 90.8±12.3 Liters; FRC: 90.2±16.6 Liters Healthy Subjects (n=7): Age: 35.4±8.7 years; FEV_1:103.2±12.4 %pred; VC: 98.8±7.2 Liters; TLC: 104.9±7.7 Liters; FRC: 101.3±3.9 Liters	• Expansion of the chest wall showed a similar increase in both groups during breathing with hypercapnia and hyperoxia • Diaphragm pressure at the end of inspiration increased similarly in both groups Patients with ankylosing spondylitis: • The abdominal compartment showed higher volume and lower rib cage volume than the control group • The peak inspiratory flow of the chest was lower in this group
Pectus excavatum		
Redlinger et al.[81] To determine if the chest wall movement and thoracic volumes differ between patients with deformities without correction of pectus excavatum (PE) and control subjects.	Pectus Excavatum (n=64) Age: 15.5 years; Weight: 58 Kg; Height: 173 cm; IMC: 19.3 Kg/m² Control Group (n=55) Age: 14.2 years; Weight: 57.9 Kg; Height: 162.6 cm; IMC: 23.5 Kg/m²	Rest • V_{cw}, V_{rcp}, V_{rca} and V_{ab}: similar in both groups Maximal Inspiration • Pectus excavatum: higher contribution of abdominal rib cage • Changes in V_{cw}, V_{rcp}, V_{rca} and V_{ab}: similar in both groups • Pectusexcavatum: lower thoracic excursion at level of the deformity of the rib cage

% pred: % predicted value; BMI: Body Mass Index; COPD: Chronic Obstructive Pulmonary Disease; *f* (min^{-1}): respiratory frequency; FEV_1: Forced expiratory volume in the first second; FRC: Functional Residual Capacity; FVC: Forced Vital Capacity; GOLD: Global Initiative for Chronic Obstructive Lung Disease; MRC: Medical Research Council dyspnoea scale; OEP: optoelectronic plethysmography; PEEP: Positive end expiratory pressure; PhAng: Phase angle; RV: Residual Volume; Te (s): Expiratory time; Ti (s): inspiratory time; TLC: Total Lung Capacity; Ttot (s): total time of the respiratory cycle; VC: Vital Capacity; VE: minute ventilation; Vee_{ab}(L): abdomen end-expiratory volume; Vee_{cw}(L): chest wall end-expiratory volume; Vee_{rc} (L): rib cage end-expiratory volume; Vei_{ab}(L): abdomen end-inspiratory volume; Vei_{cw}(L): chest wall end-inspiratory volume; Vei_{rc} (L): rib cage end-inspiratory volume; V_{ab}(L): abdominal volume; V_{cw} (L): chest wall volume; V_{cw}/ti (L/s): inspiratory flow; V_{rc} (L): rib cage volume; V_{rca}(L): abdominal rib cage volume; V_{rcp}(L): pulmonary rib cage volume.

Conclusion

OEP is a 3D system of movement analysis. It is reliable and valid to indirectly verify lung volumes, as they are obtained from direct measures of CW volume and the volume of its compartments (absolute values and theirs variations). It is a noninvasive procedure and does not require additional instruments during its use, offering real values of operational lung volumes. The applicability of this instrument is verified by the wide possibility of analysis of different disorders in different situations (static and dynamic), from laboratories to intensive care. OEP is also an appealing instrument for further analysis of the physiology of the respiratory system in several circumstances, as it enables a wide analysis of variables of volume, time, and thoracoabdominal asynchrony. This in-depth analysis provides new perspectives on the evaluation of ventilatory parameters in healthy individuals and in those with disorders, contributing to an improvement in the therapeutic strategies led by the physical therapist.

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