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ORIGINAL RESEARCH

Tidal breathing patterns derived from structured light plethysmography in COPD patients compared with healthy subjects

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Video abstract

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Purpose: Differences in tidal breathing patterns have been reported between patients with chronic obstructive pulmonary disease (COPD) and healthy individuals using traditional measurement techniques. This feasibility study examined whether structured light plethysmography (SLP) – a noncontact, light-based technique – could also detect differences in tidal breathing patterns between patients with COPD and healthy subjects.

Patients and methods: A 5 min period of tidal (quiet) breathing was recorded in each patient with COPD (n=31) and each healthy subject (n=31), matched for age, body mass index, and sex. For every participant, the median and interquartile range (IQR; denoting within-subject variability) of 12 tidal breathing parameters were calculated. Individual data were then combined by cohort and summarized by its median and IQR.

Results: After correction for multiple comparisons, inspiratory time (median tI) and its variability (IQR of tI) were lower in patients with COPD ($p<0.001$ and $p<0.01$, respectively) as were ratios derived from tI (tI/tE and tI/tTot, both $p<0.01$) and their variability ($p<0.01$ and $p<0.05$, respectively). $IE50_{SLP}$ (the ratio of inspiratory to expiratory flow at 50% tidal volume calculated from the SLP signal) was higher ($p<0.001$) in COPD while SLP-derived time to reach peak tidal expiratory flow over expiratory time (median $tPTEF_{SLP}/tE$) was shorter ($p<0.01$) and considerably less variable ($p<0.001$). Thoraco–abdominal asynchrony was increased ($p<0.05$) in COPD.

Conclusion: These early observations suggest that, like traditional techniques, SLP is able to detect different breathing patterns in COPD patients compared with subjects with no respiratory disease. This provides support for further investigation into the potential uses of SLP in assessing clinical conditions and interventions.

Keywords: structured light plethysmography, tidal breathing, chronic obstructive pulmonary disease, IE50, thoraco–abdominal asynchrony

Introduction

Structured light plethysmography (SLP) is a novel, noncontact method for assessing quiet "tidal" breathing. There is growing interest in the potential clinical uses of this technique, which has been applied to a number of clinical conditions and used to assess the response to intervention.[1–3] For example, it has recently been reported that SLP can detect changes in chest wall motion in a group of lung resection patients.[4] The reduction in the relative contribution of the chest wall to the total tidal breath was consistent with both the site and magnitude of the resection. Furthermore, a greater increase in thoraco–abdominal asynchrony (TAA) was observed in patients undergoing a lobectomy compared with resection where less lung tissue is removed. However,

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as this is a relatively new field, further published evidence confirming the utility of the technique for detecting clinical differences is limited.

Before the device can be used for more novel interventions and to compare clinical groups, there is a need to evaluate differences in SLP outputs where differences in breathing patterns are known to occur. Patterns of natural breathing at rest (or "tidal breathing") have long been reported to differ between patients with respiratory disease and healthy subjects. Evidence to support such observations has grown over the past 15 years, as a number of studies have reported the effects of conditions such as COPD on tidal breathing patterns.[5–10]

Various techniques are used to measure tidal breathing patterns, including pneumotachography (PNT), respiratory inductance plethysmography (RIP), and optoelectronic plethysmography (OEP). These vary in the source of the signal and the type of parameters that are generated. PNT, considered the gold standard for tidal breathing measurement,[11] measures airflow at the nose and/or mouth, producing a flow signal that can be integrated over time to give respired volumes. RIP involves the use of transducer bands placed around the subject to monitor excursions of the chest and abdomen over time, producing signals that, once calibrated, can provide estimates of flow and volume.[12] RIP also provides output of regional parameters such as TAA. OEP involves placement of up to 89 passive reflective markers directly on to the upper body. The movement of these markers are then recorded by multiple cameras positioned around the room and the three-dimensional (3D) coordinates of the markers are calculated.[13]

SLP does not require contact with the patient and measures tidal breathing through displacement of the thoraco–abdominal (TA) wall. A structured grid of light is projected onto the subject's chest and abdomen, and changes in the grid pattern are captured by two digital cameras and then quantified over time. From this movement-over-time trace, timing and flow-related parameters are derived. As the projected grid can be subdivided during analysis, SLP can also provide outputs relating to the displacement of defined regions of the TA wall, such as the left and right hemithorax, ribcage, and abdomen. These regional parameters describe relative contributions of each region to the achieved TA displacement and also synchrony (or asynchrony) between regions. Furthermore, a numerical measure of within-subject variability of each parameter is also provided. More detailed information on the working principles of SLP has been described by de Boer et al.[14]

This study examined whether SLP could detect differences in tidal breathing patterns between a cohort of patients with COPD and a cohort of healthy subjects, as has been reported in other studies using more traditional techniques.[5–7,9,10]

Materials and methods

Participants

All patients who were recruited to the study had previously received a clinical diagnosis of COPD from their hospital or general practitioner, in accordance with current diagnosis guidelines. Patients were recruited from general practice surgeries, hospital clinics, and hospital wards to ensure that a diverse sample of patients with the condition, and a range of severities, was included. A group of healthy subjects without a history or diagnosis of respiratory disease, and matched for age, sex, and body mass index (BMI), were also recruited. An age match was defined as an absolute difference of ≤5 years. A BMI match occurred if two individuals fell into the same BMI classification band (BMI <18.5 kg/m^2 [underweight], 18.5 ≥ BMI < 25 [normal], 25 ≥ BMI < 30 [overweight], and BMI ≥30 [obese]). A sex match was scored if two individuals shared the same sex.

Individuals were excluded from the study if they had a chest wall or spinal deformity (eg, scoliosis), an apnea hypopnea index >30 (if known), a BMI >40, or any acute or chronic condition that, in the investigator's opinion, would have limited the participant's ability to take part in the study or would likely interfere with data acquisition (eg, a cough). All participants were fully informed of the testing procedure and provided written informed consent. The study protocol was approved by the United Kingdom Health Research Authority National Research Ethics Service (study number 11/EE/00/37). The ClinicalTrials.gov identifier is NCT02626468.

Study assessments

Each participant underwent a single assessment during which 5 min of quiet "tidal" breathing was recorded using an SLP device (Thora-3Di™, PneumaCare Ltd, Cambridge, UK). Before the assessment, participants were asked to change into a close fitting white T-shirt that followed the contours of the body although they could be assessed bare chested if they preferred. Participants were instructed to sit upright in a high-backed chair. The projected grid pattern generated by the SLP device was centered on the xiphisternum with 50% of the projected squares above and 50% below this point (taken to represent the chest and abdomen, respectively).

This covered approximately the area from the clavicle to the umbilicus. Participants were then instructed not to move and to breathe naturally. Changes in the grid pattern caused by the respiratory movements of the TA wall were recorded by two cameras and quantified over time by the device. This provided a one-dimensional signal that corresponded to an individual's tidal breathing pattern and was viewed on a computer using PneumaView-3D™ software (PneumaCare Ltd) (Figure 1). This software was also used to generate a video of the 3D reconstruction of the TA wall surface.

SLP signal processing

Captured movement of the reconstructed TA surface was assessed for tracking errors caused by excessive creasing of the torso-covering white T-shirt, a lack of contrast in the projected image, or by movement. As these artifacts may affect some tidal breathing parameters, any data set which had >50% of its respiratory cycles affected by one or more of the above artifacts was excluded from further analysis. This conservative criterion was imposed to ensure that the data sets included in the study were clean.

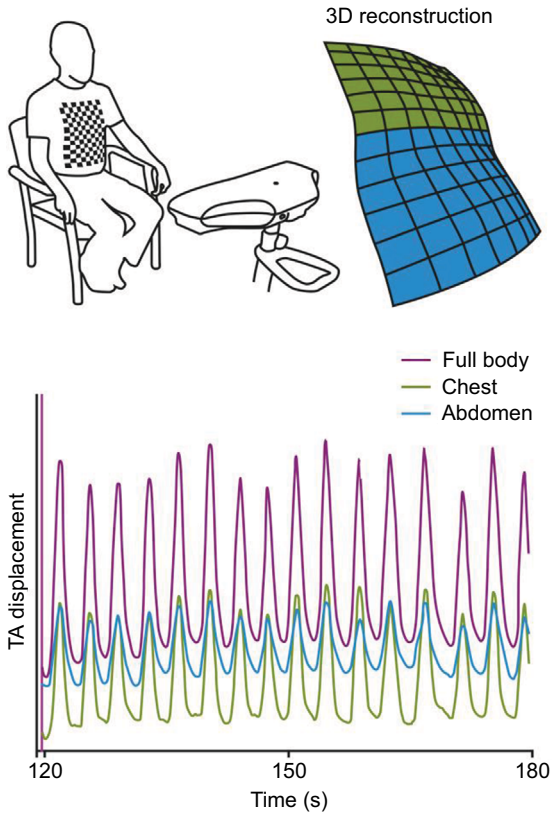

Figure 1 Working principle of SLP.
Notes: A structured grid of light is projected onto the subject's anterior TA wall (top-left). Displacements of this grid during tidal breathing are captured by two digital video cameras. This diagram shows the anterior TA wall split into two sections, one representing the thorax and the other the abdomen. Averaging the axial displacement of the surfaces corresponding to the thorax and abdomen, the thorax alone or the abdomen alone provides a means to generate one-dimensional time series corresponding to displacement of the full body, thorax, or abdomen, respectively (bottom). A 3D reconstruction of the TA wall surface is also generated during SLP (top-right). The grid top can also be divided into left and right hemithorax or any custom regions chosen for comparison.
Abbreviations: SLP, structured light plethysmography; TA, thoraco–abdominal; 3D, three dimensional.

PneumaView-3D software was used to export all SLP data accepted for further analysis into comma-separated value files, which contained information on the movement of the entire TA wall, as well as regional movements of left and right hemithorax, thorax, and abdomen. All traces were filtered using a fifth-order Butterworth band-pass filter with cutoffs at 0.05 and 5 Hz. Data were sampled at 30 Hz, which is sufficient for capturing the dynamics of TA wall movement.

A breath detection algorithm, inspired by the work of Schmidt et al and Bates et al, was used to automatically detect individual breaths on all traces.[15,16] Peaks and troughs were detected by using the zero-crossing of the first derivative of the displacement signal. To be classed as a breath, the peak-to-peak amplitude had to be >25% of the median peak-to-peak amplitude of the entire trace. Respiratory cycles with exceedingly large or small inspiratory and/or expiratory times were deemed as outliers and excluded from analysis. An inspiratory or expiratory time x_i was considered too large if its value was greater than $Q3(X)+1.5\times\text{IQR}(X)$ and too small if its value was less than $Q1(X)-1.5\times\text{IQR}(X)$, where X is the ensemble of individual inspiratory or expiratory times for each subject, $Q1$ and $Q3$ denote the first and third quartiles, respectively, and IQR is the interquartile range. To establish a one-to-one relationship between the respiratory cycles of different regional traces, cycles extracted from the movement of the entire TA wall, the left and right ribcage, thorax, and abdomen were intersected to ensure that the *nth* breath on any one trace corresponded to the *nth* breath on any of the other traces (eg, the second detected breath on the thoracic displacement trace corresponds to the second detected breath on the abdominal displacement trace). This was required for reliable and accurate quantification of regional parameters such as the relative contribution of the thorax to each breath (rCT) and TAA. The breath detection and intersection processes were also visually assessed to ensure reliability.

Tidal breathing parameters

Tidal breathing parameters included in this study were timing indices/ratios, namely respiratory rate (RR), inspiratory time (tI), expiratory time (tE), total breath time (tTot), tI/tE, and tI/tTot (duty cycle). Tidal breathing parameters relating to flow were calculated in the same way as conventional

flow-based parameters, but in this case calculated from the TA wall displacement signal (analogous to volume) and the first derivative of the TA wall displacement signal (ie, displacement rate – analogous to flow). Conventional nomenclature is used to describe the tidal breathing parameters with the addition of the suffix "SLP" to indicate the origin of the source signal. The flow-based parameters are time to reach peak tidal expiratory flow rate over tE ($tPTEF_{SLP}$/tE), time to reach peak tidal inspiratory flow over tI ($tPTIF_{SLP}$/tI), and $IE50_{SLP}$ (calculated as $TIF50_{SLP}$ divided by $TEF50_{SLP}$ where the former is "tidal inspiratory flow at 50% tidal inspiratory volume" and the latter "tidal expiratory flow at 50% tidal expiratory volume").

Further SLP parameters were calculated from regional movements of the TA wall. Here, the 3D reconstructions of the TA wall created by the SLP software were divided into an upper and lower region with equal number of grid intersections (approximately representing displacement of the thorax and abdomen) and likewise the upper region was separated into two equal top sections (reflecting displacement of the left and right thorax). Calculated regional parameters were rCT (%), left–right hemithoracic asynchrony (degrees), and TAA (degrees). Asynchronies were calculated using the Konno–Mead X–Y plots (ie, loops).[17,18] Table 1 provides a summary of the terms and abbreviations used in the study.

Statistical analysis

For each participant, every tidal breathing parameter measured over the 5 min assessment period was summarized by its median value and its IQR. Here, IQR was used as a measure of within-subject variability. For each cohort, individual data for each parameter and its variability were then combined and summarized by their median and IQR. Differences between cohorts were assessed using the Mann–Whitney *U* test (alpha level of $p<0.05$). Common language effect sizes (CLES) were calculated for parameters that differed significantly between patients with COPD and healthy subjects to further describe the ability of the parameters to distinguish COPD. CLES was selected as it does not assume normality and is easy to interpret.[19] The Benjamini–Hochberg procedure with a false discovery rate of 10% was employed to account for multiple comparisons.[20]

Table 1 List of abbreviations used for tidal breathing terminology

Abbreviations	Definitions
RR	Respiratory rate (brpm)
tI	Inspiratory time (s)
tE	Expiratory time (s)
tTot	Total breath time (s)
tPTEF/tE	Time to peak tidal expiratory flow/expiratory time
tPTIF/tI	Time to peak tidal inspiratory flow/inspiratory time
IE50	Ratio of inspiratory to expiratory flow at 50% tidal volume
rCT	Relative contribution of the thorax to each breath (%)
HTA	Hemithoracic asynchrony (degrees)
TAA	Thoraco–abdominal asynchrony (degrees)
NBreath	Number of breaths

Notes: An "SLP" suffix added to the abbreviation emphasizes that the parameter is calculated from SLP signals. SLP does not measure absolute flow or volume but measures the displacement of the TA wall (analogous to volume) and the rate of TA displacement (analogous to flow).
Abbreviations: brpm, breaths per minute; s, seconds; SLP, structured light plethysmography; TA, thoraco–abdominal.

Results

Study cohorts

Data from 31 patients with clinician-diagnosed COPD and 31 age-, BMI-, and sex-matched healthy subjects were included in the analysis. Demographics for each patient and each "matched" healthy subject are shown in Table 2. In COPD and healthy cohorts, respectively, mean age was 61.7 and 61.6 years, and mean BMI was 26.0 and 26.7 kg/m^2. Each cohort included 17 males and 14 females.

SLP-measured tidal breathing parameters

Data for each tidal breathing parameter (including their within-subject variability) are summarized in Table 3. The median (IQR) number of breaths used to calculate these data for each participant was 72 (29.5) and 62 (17) in the COPD and healthy cohorts, respectively. The Mann–Whitney *U* test identified 10 parameters that were significantly different ($p<0.05$) between the two cohorts. After accounting for multiple comparisons using the Benjamini–Hochberg procedure, all of these remained statistically significant.

Among the timing indices/ratios measured by SLP, median tI was significantly lower in COPD patients than in healthy subjects, as was its variability ($p<0.001$ and $p<0.01$, respectively). CLES for median tI was 75.1% (indicating that 75% of COPD patients had a lower median tI when compared with healthy subjects). CLES for the variability in tI was 72.8%. Similarly, both tI-derived ratios (median tI/tE and median tI/tTot; both $p<0.01$) and their variability ($p<0.01$ and $p<0.05$, respectively) were reduced in the COPD group. CLES for both median tI/tE and median tI/tTot were 72.2%. CLES for variability in tI/tE and tI/tTot were 74.3% and 68.4%, respectively.

Median $IE50_{SLP}$ was significantly higher ($p<0.001$) in patients with COPD (CLES =84.6%), while median $tPTEF_{SLP}$/tE ($p<0.01$, CLES =73.6%) and its variability ($p<0.001$, CLES =75.2%) were lower. Figure 2 provides an

Table 2 Participant demographics*

Patients with COPD (N=31)				Healthy subjects (N=31)			
Patient ID	**Age (years)**	**Sex**	**BMI (kg/m²)**	**Subject ID**	**Age (years)**	**Sex**	**BMI (kg/m²)**
COPD-01	66	Male	28.4	Healthy-01	63	Male	29.3
COPD-02	66	Male	26.6	Healthy-02	65	Male	28.3
COPD-03	63	Male	29.7	Healthy-03	66	Male	28.1
COPD-04	65	Male	21.9	Healthy-04	67	Male	24.6
COPD-05	62	Female	19.5	Healthy-05	64	Female	21.0
COPD-06	54	Male	20.7	Healthy-06	55	Male	24.8
COPD-07	66	Male	19.1	Healthy-07	67	Male	22.7
COPD-08	78	Male	18.1	Healthy-08	76	Male	18.3
COPD-09	72	Male	24.8	Healthy-09	73	Male	24.8
COPD-10	52	Male	28.0	Healthy-10	50	Male	26.7
COPD-11	63	Female	23.5	Healthy-11	64	Female	24.0
COPD-12	63	Female	23.0	Healthy-12	58	Female	20.3
COPD-13	52	Male	20.6	Healthy-13	50	Male	23.7
COPD-14	62	Male	19.7	Healthy-14	65	Male	24.0
COPD-15	35	Male	26.2	Healthy-15	40	Male	25.6
COPD-16	61	Female	18.6	Healthy-16	60	Female	22.5
COPD-17	81	Female	33.7	Healthy-17	79	Female	32.0
COPD-18	52	Female	22.7	Healthy-18	53	Female	20.1
COPD-19	72	Female	23.4	Healthy-19	70	Female	23.0
COPD-20	60	Female	25.6	Healthy-20	65	Female	26.0
COPD-21	55	Female	39.4	Healthy-21	51	Female	33.3
COPD-22	72	Female	30.9	Healthy-22	69	Female	32.9
COPD-23	70	Female	29.0	Healthy-23	67	Female	29.0
COPD-24	61	Male	31.2	Healthy-24	62	Male	33.0
COPD-25	67	Male	31.0	Healthy-25	66	Male	30.9
COPD-26	55	Male	18.7	Healthy-26	59	Male	22.9
COPD-27	53	Male	27.3	Healthy-27	53	Male	28.4
COPD-28	59	Female	38.4	Healthy-28	61	Female	37.5
COPD-29	56	Female	27.4	Healthy-29	56	Female	26.2
COPD-30	65	Male	34.0	Healthy-30	64	Male	37.6
COPD-31	56	Female	25.3	Healthy-31	53	Female	26.0
Mean ± SD	61.7±9.0	17M:14F	26.0±5.7	–	61.6±8.4	17M:14F	26.7±4.9

Note: *Data for each age-, sex-, and BMI-matched COPD patient and healthy subject are shown side by side.
Abbreviations: BMI, body mass index; COPD, chronic obstructive pulmonary disease; F, female; M, male; SD, standard deviation.

example of how $IE50_{SLP}$ could differ between a patient with COPD and its healthy counterpart. Patients with COPD also exhibited significantly greater TAA ($p<0.05$, CLES =68.5%). Table 4 summarizes the effect sizes and their interpretation.

Discussion

A number of studies have reported that patients with COPD can be differentiated from their healthy counterparts using tidal breathing patterns.[5–10] Therefore, this feasibility study investigated whether parameters derived from SLP – a novel and noncontact, light-based method for measuring tidal breathing – are also able to detect differences between breathing patterns in patients with COPD and subjects with no respiratory disease. In total, 10 SLP-measured parameters were identified which differed between COPD patients and healthy individuals; the most statistically significant of which were median $IE50_{SLP}$, median tI, and variability in $tPTEF_{SLP}/tE$. Another key observation was that, along with the reduction in inspiratory time itself, within-subject variability of tI (and each of the ratios derived from tI) was also reduced. In addition, an increased TAA (ie, asynchrony between the thorax and abdomen) and a reduced median $tPTEF_{SLP}/tE$ and its variability in the COPD group were observed.

That median $IE50_{SLP}$ was markedly increased in the COPD cohort relative to healthy subjects is a particularly interesting finding. This parameter is calculated as $TIF50_{SLP}/TEF50_{SLP}$ and can be considered analogous to the traditional "flow/volume-based" tidal breathing parameter, IE50 (the ratio of inspiratory to expiratory flow at 50% of tidal volume [TIF50/TEF50]). The effects of the COPD disease state on $IE50_{SLP}$, IE50, or related parameters have not been reported before, as such parameters have mainly been described in children with asthma or other respiratory disease.[21] The CLES associated with $IE50_{SLP}$ (84.6%, approximately equivalent to

Table 3 Comparison of SLP-measured tidal breathing parameters between patients with COPD and age-, sex-, and BMI-matched healthy subjects

Tidal breathing parameters	Healthy subjects (n=31)		COPD patients (n=31)		z-statistic	MWU test result
	Median	IQR	Median	IQR	z	*p*-Value
Timing indices and ratios						
Median RR (brpm)	14.40	5.37	15.93	7.43	1.53	0.12
IQR RR (brpm)	2.24	2.05	2.83	2.01	1.72	0.09
Median tI (s)	1.70	0.57	1.33	0.47	−3.45	<0.001***
IQR tI (s)	0.43	0.33	0.20	0.10	−3.27	<0.01**
Median tE (s)	2.43	0.84	2.40	1.13	−0.37	0.71
IQR tE (s)	0.50	0.40	0.47	0.45	−0.04	0.97
Median tTot (s)	4.17	1.44	3.77	1.56	−1.53	0.12
IQR tTot (s)	0.71	0.57	0.68	0.71	−0.44	0.66
Median tI/tE	0.70	0.11	0.58	0.28	−3.00	<0.01**
IQR tI/tE	0.17	0.06	0.11	0.06	−3.28	<0.01**
Median tI/tTot	0.41	0.04	0.37	0.11	−3.00	<0.01**
IQR tI/tTot	0.06	0.02	0.05	0.01	−2.48	<0.05*
Displacement-with-time-derived parameters						
Median $tPTEF_{SLP}/tE$	0.26	0.10	0.18	0.10	−3.20	<0.01**
IQR $tPTEF_{SLP}/tE$	0.15	0.08	0.07	0.11	−3.41	<0.001***
Median $tPTIF_{SLP}/tI$	0.52	0.11	0.53	0.12	0.01	0.99
IQR $tPTIF_{SLP}/tI$	0.17	0.08	0.18	0.11	−0.04	0.97
Median $IE50_{SLP}$	1.21	0.31	1.68	0.59	4.67	<0.001***
IQR $IE50_{SLP}$	0.41	0.24	0.51	0.34	1.96	0.05
Regional parameters (phase and relative contribution)						
Median rCT (%)	59.22	17.57	60.77	16.86	−1.01	0.31
IQR rCT (%)	3.95	2.75	4.56	2.93	−0.13	0.90
Median HTA (degrees)	1.88	1.60	2.00	1.87	0.21	0.83
IQR HTA (degrees)	2.13	0.99	2.07	1.41	0.51	0.61
Median TAA (degrees)	4.25	2.36	6.33	9.95	2.49	<0.05*
IQR TAA (degrees)	5.09	2.14	5.62	4.05	1.58	0.11
Number of breaths	62.00	17.00	72.00	29.50	1.88	0.06

Notes: Significant at *$p<0.05$, **$p<0.01$, ***$p<0.001$. Median values for all tidal breathing parameters were calculated for each participant, along with its IQR (a measure of within-subject variability). Data shown in the table are summary median and IQRs calculated by combining data for all participants in each cohort.

Abbreviations: BMI, body mass index; brpm, breaths per minute; COPD, chronic obstructive pulmonary disease; HTA, hemithoracic asynchrony; $IE50_{SLP}$, SLP-derived tidal inspiratory flow at 50% of inspiratory volume divided by tidal expiratory flow at 50% of expiratory volume; IQR, interquartile range; MWU, Mann–Whitney *U*; rCT, relative contribution of the thorax to each breath; RR, respiratory rate; s, seconds; SLP, structured light plethysmography; TAA, thoraco–abdominal asynchrony; tE, expiratory time; tI, inspiratory time; tTot, total breath time; $tPTEF_{SLP}$, SLP-derived time to reach peak tidal expiratory flow; $tPTIF_{SLP}$, SLP-derived time to reach peak tidal inspiratory flow.

Table 4 CLES and its interpretation for parameters that differed significantly between patients with COPD and healthy subjects

Hypothesis	CLES (%)	Interpretation
Median tI is reduced in COPD	75.1	In 75.1% of cases, median tI was lower in COPD
IQR tI is reduced in COPD	72.8	In 72.8% of cases, variability in tI was lower in COPD
Median tI/tE is reduced in COPD	72.2	In 72.2% of cases, median tI/tE was lower in COPD
IQR tI/tE is reduced in COPD	74.3	In 74.3% of cases, variability in tI/tE was lower in COPD
Median tI/tTot is reduced in COPD	72.2	In 72.2% of cases, median tI/tTot was lower in COPD
IQR tI/tTot is reduced in COPD	68.4	In 68.4% of cases, variability in tI/tTot was lower in COPD
Median $IE50_{SLP}$ is increased in COPD	84.6	In 84.6% of cases, median $IE50_{SLP}$ was higher in COPD
Median $tPTEF_{SLP}/tE$ is reduced in COPD	73.6	In 73.6% of cases, median $tPTEF_{SLP}/tE$ was lower in COPD
IQR $tPTEF_{SLP}/tE$ is reduced in COPD	75.2	In 75.2% of cases, IQR of $tPTEF_{SLP}/tE$ was lower in COPD
Median TAA is increased in COPD	68.5	In 68.5% of cases, median TAA was higher in COPD

Abbreviations: CLES, common language effect size; COPD, chronic obstructive pulmonary disease; $IE50_{SLP}$, SLP-derived tidal inspiratory flow at 50% of inspiratory volume divided by tidal expiratory flow at 50% of expiratory volume; IQR, interquartile range; TAA, thoraco–abdominal asynchrony; tE, expiratory time; tI inspiratory time; $tPTEF_{SLP}$, SLP-derived time to reach peak tidal expiratory flow; tTot, total breath time.

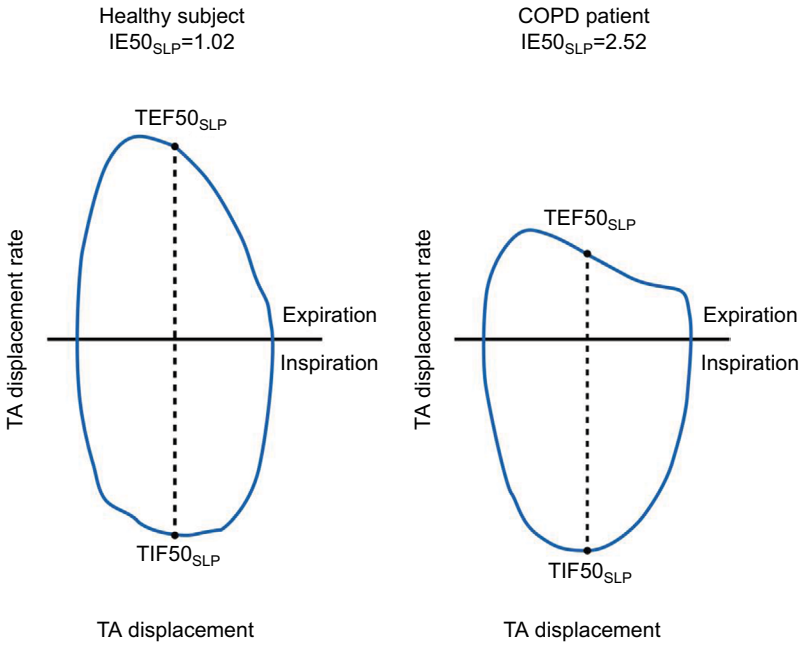

Figure 2 Illustration of how $IE50_{SLP}$ differed between a patient with COPD (right) and his or her age-, body mass index-, and sex-matched healthy subject (left).
Notes: An $_{SLP}$ suffix added to the abbreviation emphasizes that the parameter is calculated from SLP signals. SLP does not measure absolute flow or volume but measures the displacement of the TA wall (analogous to volume) and the rate of TA displacement (analogous to flow).
Abbreviations: COPD, chronic obstructive pulmonary disease; $IE50_{SLP}$, SLP-derived tidal inspiratory flow at 50% of inspiratory volume divided by tidal expiratory flow at 50% of expiratory volume; SLP, structured light plethysmography; TA, thoraco–abdominal; $TEF50_{SLP}$, SLP-derived tidal expiratory flow at 50% of expiratory volume; $TIF50_{SLP}$, SLP-derived tidal inspiratory flow at 50% of inspiratory volume.

an effect size of 1.4 had the distribution been normal) is very large, which is an indication of the ability of the parameter in distinguishing COPD from health. The current study also revealed a marked shortening of inspiratory time (ie, median tI) in the COPD cohort, and, as a consequence, ratios derived from this parameter (tI/tE and tI/tTot) were also reduced. A similar shortening of tI and associated ratios was recorded in COPD patients who participated in earlier studies employing PNT or OEP to measure tidal breathing.[6,8,10] Also, the median $tPTEF_{SLP}$/tE was reduced in patients with COPD compared with healthy subjects. This finding is consistent with several PNT studies which showed that the analogous flow/volume-based parameter (ie, tPTEF/tE) is decreased in COPD.[6,7,9,10]

Three regional SLP parameters were measured in this study, one of which (TAA) was increased in patients with COPD compared with the healthy cohort. The existence of asynchrony between different sections of the TA wall has been acknowledged for many years.[22] For example, in 1984, Sackner et al demonstrated that TAA during both inspiration and expiration was increased in COPD patients compared with normal subjects.[23] Recently, Chien et al reported the same finding and also noted that TAA in COPD patients worsens during exercise, as assessed using the 6 min walk test.[24]

Further outputs of SLP arise from calculation of within-subject variability in each of the parameters over the breathing sequence. Variability in all parameters related to tI (ie, variabilities of tI, tI/tE, and tI/tTot) as well as variability of $tPTEF_{SLP}$/tE were reduced in patients with COPD compared with healthy subjects. This study measured within-subject variability in a straightforward manner by calculating the IQR of each parameter over the course of the 5 min assessment period. More sophisticated ways of detecting variability may lead to further evaluation of this phenomenon.

A risk inherent in comparing multiple different parameters between two cohorts is that one or more statistically significant result may have occurred by chance. The Benjamini–Hochberg procedure was therefore employed to account for multiple comparisons. This approach increases the confidence with which the key findings of this study can be interpreted. Based on the data presented here, it has been proposed that assessment of tidal breathing patterns via SLP may represent a novel method to facilitate identification of patients with COPD. However, further investigation is required on the diurnal or longitudinal changes within and between individuals.

SLP is noncontact, easy to perform, requires minimal patient cooperation, and, as such, may offer certain advantages over current methods of measuring tidal breathing. PNT requires direct contact with the subject via a facemask or a mouthpiece and nose clip which, as well as causing discomfort to the patient, may also lead to a "mouthpiece effect" that can influence measured parameters.[25,26] Slippage of bands

can be a problem in RIP, leading to inaccurate readings and unusable data sets.[27,28] This technique also requires direct contact with the subject during placement and positioning of the bands. OEP is noncontact and can be used during exercise and sleep and does not require active participation of the patient;[13] however, placement of the markers is time-consuming and requires the TA surface to be exposed.[29] However, SLP can be sensitive to movement artifacts and, as such, cannot be used during activities, such as exercise or sleep. In addition, SLP does not measure absolute volume or flow but instead measures the displacement of the TA wall and the TA wall displacement rate, which are analogous to volume and flow, respectively, from which tidal breathing parameters can be derived.

The aim of this study was to determine whether SLP could detect differences in breathing patterns between patients with COPD and healthy subjects, as has been observed using traditional technologies. Validation of the SLP device was outside of the scope of this study, and further investigation will be required to determine how SLP-derived measurements are related to conventional flow-based measurements and to assess the test-retest repeatability of SLP. Such work is ongoing and preliminary findings suggest good agreement of respiratory timing indices measured by SLP and PNT, the current gold standard technique.[30]

Conclusion

It was observed that SLP is able to detect differences in tidal breathing parameters between a group of patients with COPD and an age-, BMI-, and sex-matched cohort of healthy controls. It provides a proof of concept for more extensive study of SLP-assessed breathing patterns in COPD, and in particular, into whether there is a relationship between the magnitude of any SLP-derived parameter and the severity of disease. SLP may present a potentially useful clinical tool that can be easily performed during tidal breathing and that may help identify patients with COPD.

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Author contributions

All authors contributed to study conception and/or design; interpreted the results; helped to draft, edit, and/or revise the manuscript; and approved the final version of the manuscript.

Disclosure

This paper was presented at the European Respiratory Society International Congress 2015 as a poster presentation with interim findings. The poster's abstract was published in European Respiratory Journal 2015 46: PA2283; DOI: 10.1183/13993003.congress-2015.PA2283. RI is a shareholder of and part-time paid medical advisor to PneumaCare Ltd. RW and SMF are employees of and have share options for PneumaCare Ltd. The authors report no other conflicts of interest in this work.

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