Respiratory health screening using pulmonary function tests and lung sound analysis

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ABSTRACT: Lung sounds (LS) analysis is a potential source of additional objective, noninvasive and quantitative information on the status of the pulmonary system. We have examined the hypothesis that the addition of lung sounds analysis to spirometry increases the sensitivity of objective population screening, as compared to the use of spirometry alone.

Questionnaires, spirometry and lung sounds were obtained in 493 active workers. Lung sounds analysis consisted of the averaged power spectra of breath sounds, measured separately during inspiration and expiration at four standard locations over the trachea and the chest-wall.

Of the 493 subjects, 91 had an obstructive lung disease, including 27 with chronic bronchitis identified by a history of prolonged cough and sputum production but with normal spirometry. Twelve additional workers had a restrictive lung disease. Abnormal spirometric results were found in 74 of the patients. Abnormal lung sounds analyses were found in 54 patients, including 14 of the chronic bronchitis cases, so that the overall sensitivity of objective screening tests increased from 71% to 87% by combining the two tests. Thirty three of the subjects considered normal by evaluation of their questionnaire and spirometry had abnormal lung sounds. Of the twenty four who were re-evaluated 12–18 months after the first tests, three had developed a lung or heart disease.

We conclude that the combination of spirometry and lung sounds analysis significantly increased the sensitivity of detection of pulmonary diseases by objective tests, and provided an early sign of lung disease that was not detected by spirometry alone.

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Pulmonary screening is used extensively in industry, insurance related check-ups, general population surveys and routine clinical practice. Since spirometry is relatively simple, non-invasive and inexpensive, it is often the only objective screening test, especially when there are concerns about cost and/or radiation exposure. In many pulmonary surveys there is minimal physician involvement. X-ray films, physical examination and extended lung functions tests are employed in mass screening only in special cases. Spirometry is primarily useful for identifying patients with significant expiratory airflow limitation or reduced lung volumes. Spirometry alone results in a substantial number of subjects with lung abnormalities remaining undetected [1]. The reliability of responses to a pulmonary questionnaire, another commonly used method, is limited [2].

Auscultation of the lungs by trained pulmonologists, as part of screening for pulmonary disease, although desirable, is often not practical, and the general emphasis on objective measurements and quantitative, record-

able data has diminished the perceived value of pulmonary auscultation. However, lung sounds are normal recurring signals, their detection is noninvasive, and no radiation or patient discomfort is incurred during either auscultation or recording. Unlike standard pulmonary function tests (PFT), only minimal subject co-operation is necessary for measuring lung sounds. On the other hand, the acoustic signal is both complex and short-lived. Reliable and convenient methods for recording and analysing acoustic signals have not, so far, been available. The potential benefits of lung sounds measurements, and the technical ability to process acoustic information, has stimulated research into methods of analysing lung sounds [3]. One of these methods, phonopneumography (PPG), has been used for the mass screening study reported here.

Prior to the adaptation of PPG for clinical use, it was necessary to acquire substantial further experience with sound spectral patterns both from normal subjects and from patients with a variety of lung diseases. Previous

studies of the characteristics of normal lung sounds [4], wheezes [5], and the temporal stability of lung sounds [6], provided the basis for recognition of most common spectral patterns. PPG spectra, recorded repeatedly on the same day and then again seven days later, showed negligible temporal variability. Thus, there are adequate data to demonstrate that lung sounds analysis can be performed reliably using modern signal processing methods.

In the present study, we have tested the hypothesis that when quantitative analysis of continuous lung sounds (*i.e.* basic tracheal and chest-wall sounds and wheezes), using PPG, is added to spirometry, it significantly improves the sensitivity of objective lung health screening. The PPG was especially useful and important in two distinct subgroups: 1) patients with chronic bronchitis according to their questionnaire replies but with normal PFT (as opposed to patients with chronic obstructive pulmonary disease (COPD) identified mainly by PFT abnormalities) [7], and 2) subjects who appeared to be healthy by questionnaire and spirometry, in whom the only evidence of abnormality at the time of screening was in their lung sounds.

Subjects

We studied 493 workers (385 men and 108 women, 21–77 yrs of age), volunteers from seven work places: two fertilizer factories ($n=157$), a power plant ($n=81$), three police units ($n=68$), a local municipality ($n=99$), medical school ($n=67$), and a medical centre ($n=21$). The tests were carried out at the workplaces, during work hours, and required approximately 30 min per subject. Table 1 presents some details concerning the subjects.

Table 1. – Personal data of the subjects ($n=493$)

Subjects	n	Age yrs	Height cm	Weight kg	Pack- yrs
Healthy males					
Smokers	166	45±11	172±7	80±15	25±17
Nonsmokers	132	43±11	174±7	79±12	
All	298	44±11	173±7	80±13	
Non-healthy males					
Smokers	62	47±12	172±7	77±13	34±21
Nonsmokers	25	46±12	175±6	83±13	
All	87	47±12	173±7	79±13	
All males	385	45±11	173±7	79±13	
Healthy females					
Smokers	22	45±11	162±7	67±13	19±15
Nonsmokers	68	39±11	161±6	62±10	
All	90	40±11	161±6	63±11	
Non-healthy females					
Smokers	6	43±14	159±4	70±22	20±9
Nonsmokers	12	41±12	163±7	67±14	
All	18	42±12	162±6	68±17	
All females	108	41±11	161±6	64±12	
All subjects	493	44±12	170±8	76±15	

Data are presented as mean±SD.

Methods

Spirometry and lung sounds measuring system

The test equipment was built into a small trunk for convenient transport and use. Flow was measured with a pneumotachograph (Fleisch NO. 3, Gould Inc., Cleveland, Ohio, USA) coupled to a differential pressure transducer (MP-45±2 cmH₂O, Validyne, Northridge, CA, USA). The analogue signal was converted to digital values with a multi-channel 12 bit A/D converter (MacADIOS II, GW Instruments, Cambridge, MA, USA) at a sampling rate of 100 Hz. Volume and flow calibrations were made daily with a calibrated 3 l syringe. Flow and volume resolution and frequency response were tested, and found to be well within the guidelines of the American Thoracic Society (ATS) [8]. Parametric data (*i.e.* forced expiratory volume in one second (FEV₁), forced vital capacity (FVC), forced mid-expiratory flow (FEF_{25-75%}), forced expiratory flow when 25, 50 and 75% of FVC has been exhaled (FEF_{25, 50, & 75%}) and FEV₁/FVC) were calculated from the best effort, and stored for further analysis, together with a graphic display of the flow-volume curve. The parametric data were analysed as percentage of predicted [9]. Data analysis and recording of parameters were performed on a microcomputer (Macintosh SE, Apple Corp.) using Lightspeed C and Fortran languages.

The pneumotachograph flow signal was used to generate a trigger for acoustic data acquisition. Four identical custom-made piezoelectric sensors were affixed at standard locations on the trachea and chest-wall, using circumferential rubber strips [4]. Sensors were designated as follows: trachea (TR), right anterior chest (CR), right and left lung bases posteriorly (BR and BL, respectively). The signal from each sensor was amplified, band-pass filtered (75–2,000 Hz) and digitized at 4 kHz per channel. Signal processing and analysis were performed as described previously [4], but with current computer capabilities breath-by-breath on-line power spectra were calculated using a Fast Fourier Transform (FFT) of 0.512 s segments of the lung sounds, sampled simultaneously from all sensor locations. The sound spectra of segments from 6–15 inspirations, and from a similar number of expirations, were averaged and displayed on-line as log power vs frequency. The operator of the system terminated the averaging of spectra once the breath-to-breath variability of the displayed curves diminished. The number of breaths per averaged spectrum was >6 and ≤15, so that the total duration of analysed data from the four channels was 24–60 s. Average spectra of inspiratory, expiratory and background sounds were obtained for each of the sensors, and stored in digital form for further off-line analysis.

PFT and LS data management was performed using the HyperCard (Apple Computer Inc.) and QuickBasic (Microsoft Co.) programming languages. Magnetic tape recording (AD-F360, Aiwa Co., Japan) of lung sounds was conducted simultaneously throughout the PPG data acquisition for subsequent auditory review. The two

channels of the stereophonic tape recorder were used. One channel continuously recorded the output of the tracheal sensor, whilst the sounds from the chest-wall sensors were sequentially recorded on the other channel.

The overall duration of the magnetic tape recording was 12–15 min per subject (*i.e.* 12–15 min of tracheal sounds on one channel and 4–5 min of sounds from each of the chest-wall sensors on the other channel).

The slope, intercept and regression coefficient of the best-fit lines of the log amplitude *vs* log frequency curves of the average spectra were calculated off-line from each of the chest-wall sensors. Two distinct linear segments were found in the chest-wall spectra of normal subjects: one in low frequencies, from 75 Hz (the cut-off frequency of the high-pass filter) to 150–180 Hz, which is the position of a deflection in the spectral curve (Fdef). The other extending from Fdef to the highest frequency in which the power of the acoustic signal is non-zero (Fmax) (fig. 1). The normal ranges of values of the slope of the second regression line and its intercept with the frequency axis (*i.e.* Fmax), were based on data from a previous study on the spectral characteristics of normal breath sounds [4], and are given in table 2. The regression coefficient of the best-fit line (R) and the ratio between the total power in the actual spectrum and the power under the regression line (RAT) were calculated, in order to verify the validity of the linear fit. The area, A1, under the logarithmic spectral curve from Fdef to Fmax, was calculated by integrating the spectral values with a logarithmically decreasing width of the integration variable (*i.e.* log frequency). This integral was divided by the area, A2, of the triangle under the corresponding regres-

Fig. 1 — Normal PPG power spectral curve (CR position, expiration) after smoothing with a running average filter of five points, presented as log power (arbitrary units) *vs* log frequency. Regression lines are superimposed. The normal values of the slopes and maximal frequencies are given in table 2. PPG: phonopneumography; CR: right anterior chest; Exp: expiration. Fdef: Deflection frequency; Fmax: maximal frequency. The text at the bottom of the figure indicates the identification code of the patient, the pick-up location (see text), and the respiratory phase.

Table 2. — Normal values of slope and Fmax of regression line

Pick up Location	n	Slope dB·oct ⁻¹		Fmax Hz	
		Inspiration	Expiration	Inspiration	Expiration
CR	6	13.2±4.2	15.7±4.5	604±302	406±206
BR	10	12.8±1.7	13.1±1.3	446±143	286±53
BL	8	12.3±2.5	12.9±2.6	475±115	284±47

Data are presented as mean±SD. CR: right anterior chest; BR: right base of lung; Fmax: maximal frequency. Slope dB·oct⁻¹: Slope of regression line from Fdef to Fmax shown in Fig. 1, in dB/octave. (From [4]).

sion line. RAT was defined as: $RAT = 1 - |1 - A1/A2|$ and can have the value of one at the most, when the two areas are identical. In a previous study these parameters were found [4], to provide adequate quality assurance of the linearity of the spectral curve. In that study, spectra were considered normal if the values of both R and RAT were greater than 0.75, and their combined value (*i.e.* R+RAT) was greater than 1.7 [4]. Curves that did not meet these criteria, displayed slope irregularities or had peaks of power, were considered abnormal and potentially associated with lung pathology.

Procedure

A session with each subject included anthropometric measurements, PFT, completion of the questionnaire, and PPG with simultaneous magnetic tape recording. Measurements were made in a quiet but not soundproof room. Spirometry was performed first, according to the ATS recommendations [8]. The questionnaire was a Hebrew adaptation of the standard ATS questionnaire, modified for interactive use by an interviewer on a computer using the HyperCard program [10, 11]. The sound sensors were then attached for PPG measurements. Subjects were instructed to breathe through the pneumotachograph whilst observing an analogue flow meter, and to generate inspiratory or expiratory flows a little greater than the threshold value of 1.0 l·s⁻¹. A summary of the PFT results, questionnaire responses and PPG data was stored in digital form on 3.5" diskettes.

Data analysis methods

PFT interpretation was accomplished automatically, immediately after the completion of the PFT test, using a scoring method (appendix) based on deviations from predicted values. The questionnaire was evaluated on-line, using a computerized algorithm. Abnormal LS spectral patterns were identified by independent off-line review of the parameters and graphic displays, (*e.g.* figs 1 and 2). All magnetic tape recordings of lung sounds were reviewed, off-line, by experienced listeners, and their findings compared to the graphic results.

All subjects with an abnormal PFT (score ≥3) and/or positive questionnaire with or without abnormal lung sounds, were referred for further independent evaluation by one of the authors (A.E.R.) in the Pulmonary Department of Rambam Medical Center. This evaluation consisted of an interview, physical examination, repeat PFT

Fig. 2 – Pathological PPG power spectral curves after smoothing with a running average filter of five points, presented as log power (arbitrary units) vs log frequency. a) Primarily narrow frequency peaks; b) Primarily wide frequency peaks. Arrows indicate some of the more prominent peaks. Insp: inspiration; Exp: expiration. PPG: phonopneumography; BR: right lung base; CR: right anterior chest. SR: Interscapular region. The text at the bottom of the figure in each panel indicates the identification code of the patient, the pick up location (see text), and the respiratory phase.

including lung volumes and airway resistance measurements, and in selected cases chest X-ray films and/or diffusion capacity measurements. A clinical summary, including a general statement on each subject's respiratory health status, was sent to his/her physician. Subjects with normal PFT values, normal LS, and no respiratory symptoms were considered healthy and were not, in general, subjected to any further evaluation. A small subset of the normal group was evaluated independently by an additional pulmonologist, as a quality control measure. There were no significant discrepancies between the two clinical consultants.

Results

One hundred and five (21%) of the 493 subjects had clinical evidence of pulmonary abnormalities. Seventy four (71%) of them had abnormal PFT values, whilst the remaining 31 (30%) had normal PFTs, (table 3). The diagnoses among the patients with abnormal PFT values were COPD (n=59), restrictive lung disease (RLD) (n=12), asthma (n=1), congestive heart failure (n=1), and emphysema (n=1). Twenty seven (87%) of the patients with normal PFT values reported symptoms compatible with a diagnosis of chronic bronchitis (CB). Three others had very mild COPD with minimal spirometric findings and one had asthma. All diagnoses were made according to established ATS criteria [7–9].

The spectral patterns of the sounds from the four sensors were the same as described previously in normals as well as in subjects with lung ailments [4, 5]. In the normals, tracheal sounds (one sensor) have a wide band noise pattern. The chest-wall spectra (three sensors) have the characteristic of lowpass filter, with higher intensities during inspiration than during expiration. Figure 1 is an example of a normal inspiratory chest wall PPG power spectral curve (in a log-log presentation). Typical features are: 1) initial small linear decline in the low frequency range, and 2) subsequent faster linear decline of power with increasing frequency. Some of the curves' parameters are shown. Several examples of abnormal spectra are shown in figure 2. The most frequent deviations from normal were extra peaks of power in the higher frequency spectrum. These added peaks were

usually narrow and sharp, and often corresponded to wheezes that were easily heard on the recorded sounds [5]. In some subjects, the extra peaks were wider, due to the averaging of wheezes with varying frequencies or to the presence of multiple non-musical sounds with a narrow band spectrum. Other PPG spectral abnormalities included non-linearity of the regression lines, stair-shaped curves, and an extension of the frequency range beyond the normal maximal frequency.

The number of subjects with an abnormal PFT and/or LS in each disease category is shown in table 3. Of the 105 patients with lung diseases, 54 (52%) had an abnormal PPG. Thirty (49%) of the COPD patients had abnormal lung sounds. Fourteen (52%) of the CB patients, 6 (50%) of the RLD patients and the two asthmatics also had abnormal PPGs. In addition, 32 (8%) of the 388 normal subjects (*i.e.* designated as healthy by the pulmonologist) had abnormal PPG findings. In one further case, both PPG and PFT were abnormal, but the consultant pulmonologist concluded that the patient was healthy.

All 32 presumed "false-positive" cases were invited for a follow-up evaluation 12–18 months after their first test. In 21 of the 24 follow-up examinations completed to date the PPG abnormality persists. Lung or heart disease manifested itself in 3 (13%) of these (diagnoses: restrictive lung disease; COPD; congestive heart failure). The other 18 subjects continued to have normal spirometry results. Some of them reported symptoms of cough episodes and sputum production, but for shorter periods than required for a definite diagnosis of CB.

Obesity was the diagnosis in 5 of the 12 patients who had a restrictive pattern in their PFT results (table 4). Four of these had normal breath sounds and one had peaks in the inspiratory spectra obtained from CR and BL. Two additional subjects whose initial PFTs had a restrictive pattern, were subsequently found to be normal on follow-up examination. Both had normal breath sounds patterns. Another subject had a restrictive PFT pattern following a thoracotomy and drainage of empyema. This subject was clinically classified as having normal lungs, and he had normal breath sounds spectral patterns. Two subjects had a restrictive lung disease (fibrosis). Both had peaks, corresponding to wheezes or squeaks, in their spectra. One subject had severe

Table 3. – Health condition of the 493 subjects

Clinical Condition	PFT		LS		PFT and/or LS		Total
	Normal	Abnormal	Normal	Abnormal	Normal	Abnormal	
Healthy	381	7	355	33(1*)	349	39	388
CB	27	0	13	14	13	14	27
Asthma	1	1	0	2	0	2	2
COPD	3	59	32	30(2#)	1	61	62
RLD	0	12	6	6	0	12	12
Other	0	2	0	2	0	2	2
Total	412	81	406	87	363	130	493

PFT: pulmonary function tests; LS: lung sounds analysis; *: abnormal PFT; #: normal PFT; CB: chronic bronchitis; COPD: chronic obstructive pulmonary disease; RLD: restrictive lung disease.

Table 4. – Spirometry and lung sounds in 12 subjects with restrictive pulmonary function pattern

Subject No.	Sex	Age yrs	Height cm	Weight kg	First FEV ₁ %	First FVC%	FU FEV ₁ %	FU FVC%	Pack-yrs	Lung sounds	Clinical diagnosis
1	M	63	173	98	83	79	-	-	22	Normal	Obesity
2	M	57	165	90	70	69	77	77	64	Normal pattern on FU	Obesity
3	M	40	170	99	76	77	-	-	0	Normal	Obesity
4	M	65	154	84	75	72	-	-	0	Insp. peak CR, BL	Obesity
5	M	46	170	88	82	73	84	79	0	Normal	Obesity
6	F	25	157	44	75	77	84	80	0	Normal	Healthy on FU
7	M	58	183	81	76	68	81	79	18	Normal	Healthy on FU
8	M	33	172	80	67	85	76	79	9	Normal	S/P Thoracotomy (empyema)
9	M	57	172	67	70	70	67	75	0	Peak in CR-insp	RLD
10	M	51	179	86	75	74	-	-	39	Exp. peaks (wheezes) all points	RLD
11	M	55	178	94	76	78	85	82	5	Abnormal (non-linear CR-insp)	Severe scoliosis and obesity
12	M	28	183	60	79	79	87	87	24	Peaks in BR-exp	Chronic bronchitis in FU
Mean					75	75	80	80			
SD					4.7	5.0	6.6	3.6			

FU: follow-up; FEV₁%; forced expiratory volume in first second (% of predicted); FVC%: forced vital capacity (% of predicted); CR: right anterior chest; BL: left lung base; BR: right lung base; Insp: inspiratory; Exp: expiratory; RLD: restrictive lung disease; S/P: status post.

scoliosis and obesity. His inspiratory breath sounds spectrum over CR was abnormal with a step-like curve, which is compatible with broncho-vesicular breath sounds. The last subject in the group had normal PFT results on follow-up examination, but reported cough and sputum production over a period, long enough to classify him as having chronic bronchitis. This patient had distinct peaks (wheezes) in the spectra from BR during expiration.

Cigarette smoking was common among the subjects in this study. Smokers were 47% of the 370 subjects who had both normal PFT and normal breath sounds. Among the 44 subjects who had normal PFT but abnormal breath sounds, smoking was reported by 66%. The difference between the groups was statistically significant ($p < 0.01$) by Student's *t*-test for proportions. The smoking history among the smokers in the two groups was similar (24.4 ± 16.6 and 24.3 ± 12.7 pack-year, respectively).

Combining spirometry and PPG to identify those patients with pulmonary disease among the study population, led to detection of 91 (87%) of them. This means that by adding PPG to conventional screening, the sensitivity of objective detection of patients with lung diseases was increased by 23%. The differences between the sensitivity of spirometry (74 out of 105 or 71%), and the sensitivity of PPG (54 out of 105 or 51%), *versus* the sensitivity achieved by combining both of these objective methods in this sample (91 out of 105 or 87% for PFT+PPG) are statistically significant ($p < 0.001$, by confidence interval and by *t*-test).

Discussion

The purpose of the present study was to evaluate the usefulness of adding spectral measurements of lung sounds

to conventional respiratory screening of workers (*i.e.* active subjects in relatively good health). With any screening programme, the most relevant question is "did we identify all those who were ill?". The goal is to minimize the false negative rate. Erroneous identification of a normal subject as being ill (false positive) is not desirable, but usually less significant than overlooking a sick subject (false negative). In addition, the validity of objective and quantitative test results is superior to that of information based on patient symptoms and history obtained through questionnaires. The value of this approach was demonstrated by the significant numbers of workers found to have COPD although they denied respiratory symptoms on their questionnaires. Therefore, we focused our attention on the sensitivity of the objective screening tests - spirometry *versus* spirometry plus lung sounds (LS) analysis.

The observation that adding another test increased the overall sensitivity is not surprising, as this is a common finding whenever a relevant test is added to the screening procedures. The clinical and public health significance of earlier detection of lung diseases is apparent, in particular when cessation of cigarette smoking or occupational exposure are effected through the identification of the disease process. The overall cost-benefit relationships of adding the new LS analysis test to the screening regime was not evaluated in this study.

Breath sounds have long been used to diagnose and evaluate the severity of lung diseases. SCHNEIDER and ANDERSON [12] correlated the physical diagnosis findings with ventilatory functions in emphysema patients, and ranked first in importance the observation of decreased breath sounds. WOOLF and SAMAD [13] found a good match between the intensity of breath sounds over the chest-wall with the darkness of the corresponding lung regions in chest radiograms. McFADDEN *et al.* [14] used

auscultation and physiological measurements to follow the progress of resolution of an acute asthma attack. The presence of wheezes was most persistent, and extended well after subjective improvement was reported by the patient. These studies and others [3] demonstrated the usefulness of auscultation in the identification of lung diseases. In the present study, two new features were added: the use of computerized analysis of the sounds, and the attempt to evaluate a group of subjects who were not very ill, *i.e.* the vast majority of those who were classified as having a lung disease had only a mild illness that did not impair their ability to work. The identification of such patients is more difficult than the comparison of a group of patients with well-defined pulmonary ailments to a group of normals, as has usually been done in the past. Based on the vast previous knowledge on auscultation, dating from Laennec until today, it is possible to expect that computerized breath sounds measurements will be useful in identifying lung patients, once it is refined to the point where it becomes compatible with careful auscultation. The data in this study seem to represent a step towards achieving and validating this goal.

One of the most significant results is that 14 of the 27 patients with a history compatible with chronic bronchitis, but normal spirometry, had abnormal lung sounds. Thus, LS measurements provided objective evidence of lung pathology in approximately half of the CB patients. The LS abnormalities of CB has not, to our knowledge, been described previously. The majority of these LS abnormalities were occasional wheezes, and in some patients wheezes were present in only one or two breaths during the 12–15 min of measurements. These wheezes were readily detected by this computer-based method of analysis. Most wheezes were also identified by careful listening to the recorded magnetic tapes of the sounds analysed by the computer. It is conceivable that in a conventional clinical setting, some of the wheezes are likely to be overlooked, even by expert chest auscultation, considering the fact that the listening rarely lasts for more than a few breathing cycles.

Since 14 of the 27 CB patients (52%) had normal spirometry but abnormal PPG, it appears that airway abnormalities not detectable by standard spirometry can generate abnormal acoustic signals. The mechanism of this phenomenon is as yet unclear. The importance of small airways abnormalities has been stressed by many clinicians, and it is known that they are often difficult to identify with certainty from PFTs [15]. The small airway narrowing may, however, lead to regional flow limitation and generation of wheezes when air flows through some pathways, whilst other airways are sufficiently patent to allow normal overall maximal flows. Another possible mechanism is that changes in the amount and/or composition of mucous secretions in some of the airways induces the generation of wheezes, whilst not yet sufficient to cause an obstructive FT pattern. Although chronic bronchitis is currently defined solely by the patient's medical history, our results suggest that LS measurements may provide an objective support for a diagnosis of CB in a significant number of the cases. The

use of more sensitive sound detectors, longer detection periods and advanced signal processing, may have facilitated the detection of abnormal acoustic signals from some of these patients. The higher proportion of smokers among the normal PFT subjects who had abnormal breath sounds reflects the fact that most of the CB patients were smokers. This observation is also compatible with a study by LAIRD *et al.* [16] who described changes in breath sounds after exposure to cigarette smoke. The pathophysiological mechanisms and significance of abnormal LS in CB is yet to be studied in detail.

Thirty three subjects who were designated as normal from their clinical assessment had abnormal lung sounds. This group constitutes the "false positive" outcome of LS measurements. To further evaluate this finding, we invited these workers for follow-up study 12–18 months after the original screening and clinical assessment. Twenty four consented and were completely re-evaluated by questionnaire, spirometry, PPG, and a clinical assessment by the pulmonologist. Abnormal LS were found again in 21 (88%) of the subjects. Three subjects had developed lung or heart disease with reduced PFT values, and some of the other subjects reported cough and sputum production, but for shorter periods than needed to be defined as CB. Therefore, it seems likely that an abnormal PPG finding represents an early or mild phase of lung disease that has not yet produced either detectable clinical symptoms or abnormal spirometry.

The findings in the 12 subjects who had a restrictive pattern in their PFTs (table 4) show that the four patients who had significant active restrictive lung diseases also had abnormal lung sounds. Among the six other subjects who had a restrictive pattern due to obesity ($n=5$), or previous thoracotomy ($n=1$), and the two subjects who were judged normal in follow-up assessments, seven had normal LS and only one had an abnormal pattern. One subject, who initially had an abnormal LS pattern, had normal LS on follow-up LS measurements. All the patients with a restrictive pattern due to lung abnormalities had abnormal breath sounds.

Overall only 50% of the patients in this study were found to have LS abnormalities by the PPG. This is probably due to two major causes: 1) some lung diseases are not associated with abnormal LS. 2) the PPG is not sufficiently sensitive to detect all LS abnormalities. The first possibility is certainly plausible, particularly among working subjects with mild to moderate diseases, as in the population studied here. In addition, the PPG methodology could be improved. PPG results were compared to the independent interpretations made by three experienced individuals, who listened to the sounds recorded on magnetic tape while the computerized analysis was in progress. Under these conditions, PPG was found to be superior to the human ear for detecting continuous adventitious sounds, such as wheezes. This was especially true when a faint wheeze was present in just a few breaths. On the other hand, the PPG, in the form used for this study, is not suitable for the detection of crackles. Since crackles were detected upon listening to the taped sounds, it is possible that

adding automated crackle detection [17] to PPG would further increase the overall screening sensitivity.

We conclude that LS measurement provides additional, useful noninvasive objective and quantitative information about the respiratory system. Used for screening in conjunction with spirometry, LS measurements improve the sensitivity of identifying lung disease in an incipient stage, prior to the onset of respiratory symptoms or to changes in spirometry in CB patients. LS measurements may be useful in pulmonary health screening programmes.

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Appendix

Calculation of PFT score

FEV ₁	<85% of predicted = +1
FEV ₁	<80% of predicted = +4
FVC	<85% of predicted = +1
FVC	<80% of predicted = +4
FEV ₁ /FVC	<90% of predicted = +3*
FEF _{25-75%}	<65% of predicted = +1
FEF _{25-75%}	<50% of predicted = +4

* If FVC is greater than 105% of predicted, then add 3 points only if FEV₁/FVC <85% of predicted.

This score is intended to separate normals from patients with abnormal PFT values. It does not indicate the type or the severity of the abnormality. The values were summed, and PFT results with a score of ≥ 3 were considered abnormal.

References

1. Taplin GV, Tashkin DP, Chopra SK. – Early detection of chronic obstructive pulmonary disease using radionuclide imaging procedures. *Chest* 1977; 71: 567–575.
2. Samet JM. – A historical and epidemiologic perspective on respiratory symptoms questionnaires. *Am J Epidemiol* 1978; 108: 435–445.
3. Loudon R, Murphy RLH, Jr. – Lung sounds. *Am Rev Respir Dis* 1984; 130: 663–673.
4. Gavriely N, Palti Y, Alroy G. – Spectral characteristics of normal breath sounds. *J Appl Physiol: Respirat Environ Exercise Physiol* 1981; 50: 307–314.
5. Gavriely N, Palti Y, Alroy G, Grotberg JB. – Measurement and theory of wheezing breath sounds. *J Appl Physiol: Respirat Environ Exercise Physiol* 1984; 57: 481–492.
6. Mahajna M, Gavriely N. – The variability of spectral content of normal lung sound. 16th International Conference on Lung Sounds, Sept. 30–Oct. 2, 1991, Veruno-Arona, Italy.
7. American Thoracic Society. – Chronic bronchitis, asthma and pulmonary emphysema. A statement by the committee on diagnostic standards for nontuberculous respiratory diseases. *Am Rev Respir Dis* 1962; 85: 762–768.
8. American Thoracic Society – Standardization of spirometry - 1987 update. *Am Rev Respir Dis* 1987; 136: 1285–1298.
9. Quanjer PhH, (Ed.) – Standardized lung function testing. *Bull Eur Physiopathol Respir* 1983; 19 (Suppl. 5): 7–10.
10. Ferris BG. – Epidemiology standardization project. *Am Rev Respir Dis* 1978; 118 (part. 2): 1–120.
11. Nissan M, Rubin AE, Cugell DW, Gavriely N. – Respiratory symptoms questionnaire in Hebrew for use in industrial epidemiology studies. *Harefuah* 1990; 119: 133–135.
12. Schneider IC, Anderson AE Jr. – Correlation of clinical signs with ventilatory function in obstructive lung disease. *Ann Intern Med* 1965; 62: 477–485.
13. Woolf CR, Samad IA. – Comparative evaluation of methods of assessment of chronic obstructive pulmonary emphysema. *Can Med Assoc J* 1968; 99: 940–943.
14. McFadden ER Jr, Kiser R, deGroot WJ. – Acute bronchial asthma. *N Engl J Med* 1973; 288: 221–225.
15. Macklem PT. – Obstruction in small airways: a challenge to medicine. *Am J Med* 1972; 52: 721.
16. Laird, CW, Homburger, F, Ishikawa S. – Breath-sound changes after cigarette smoking. *Lancet* 1974; 7861: 808.
17. Arakawa K, Harashima H, Ono M, Mori M. – Non-linear digital filters for extracting crackles from lung sounds. In: *Frontiers of Medical & Biological Engineering*. 3. 1991; pp. 245–257.