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WHEN SPIROMETRY OR WHOLE BODY PLETHYSMOGRAPHY AND LUNG COMPLIANCE TEST IS INDICATED?

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1.0 INTRODUCTION

The detection of lung function disturbances has a great value in health and disease. We use the lung function tests in the diagnosis and monitoring procedures in different lung diseases and in general medicine. These methods are also very useful in qualification of patients before thoracic surgery interventions, to determine the grade of respiratory impairment in patients and in epidemiological studies evaluating the negative influences of outdoors or indoors environment factors in workers and in inhabitants of different regions.

The analysis of lung ventilation disturbances concerns the degree of impairment and especially the mechanisms, which are responsible for respiratory insufficiency. The identification of lung function disturbances helps us very often in the diagnostic procedure and in the decision about therapy. Analysis of lung mechanic impairment is the first important step of diagnostic procedures in lung diseases.

According to guidelines of the European Respiratory Society 1993 [2] the diagnostic procedures of lung mechanics disturbances include spirometry (VC, FEV₁), the registration of maximal expiratory flow-volume loop and the calculation of maximal expiratory flow rates (PEF, MEF₅₀, MEF₂₅), and the measurement of functional residual capacity (FRC) and airway resistance (Raw) with whole body plethysmography. Estimation of static lung compliance (Cst) especially in the interstitial lung diseases is needed.

In the Lung Function Department of the Institute of Tuberculosis and Lung Diseases in Warsaw the annual number of spirometry measurements is about 7000, bodyplethysmography analysis about 2000, lung compliance tests about 1000 and lung diffusion tests about 1000 pro year.

2.0 SPIROMETRY

From theoretical point of view the ventilation disturbances of the lung is a result of impairment of elastic and/or non-elastic resistances of respiratory system.

For these reason two important methods as spirometry and bodyplethysmography are very often used. We understand spirometry as a first step in the analysis of lung mechanic disturbances but this must be very often supplemented and verified by bodyplethysmography. These two methods are complementary and no one can be replaced through the another. The advantage of spirometry is the relative exact measurement of bronchial obstruction with relatively inexpensive equipment. Negative sign is the necessity of very good cooperation of the proband during testing of maximal forced expiration.

The spirometric equipments for ventilation measurement are divided in two groups.

To the first group of spirometers belongs the volumeter for **direct** estimation of lung volumes. This type of spirometer is very frequently used in hospitals and in outpatient's clinics. With this apparatus we can measure the static and dynamic spirometric parameters. The static values are vital capacity (VC) and their components (TV, IRV, ERV) and the dynamic values, which contain the volumes in relation to time like FEV₁, FEV₁ %VC ratio (Tiffeneau Index). (Fig. 1a).

In the second group there are so called computerized spirometers, which today substitute volumetric devices. The modern spirometer consists of two important compounds: the pneumotachograph to appropriate measuring of flow in the airways and a computer device for mathematical calculation (integration) of the volume (VC). So the volume measurement with this device is a indirect procedure.

The recording of classical spirometry is in fact an examination of relation between volume and time (V/t). The recording of the lung mechanics parameters with the use of electronic spirometer is an analysis of volume/flow measurement (V/V') (Fig. 1b).

Today the recording of the maximal expiratory flow-volume loop and estimation of the maximal expiratory flow rates (MEF₅₀, MEF₂₅) and the FVC are the most frequent tests used in the diagnosis of airflow obstruction and in the analysis of FVC diminishing (restrictive defect).

With the use of FVC or VC measurement we can speculate only roughly about the restrictive ventilatory defect. According to the statements of the European Respiratory Society [2] the restrictive ventilatory defect is better described by reduction of TLC than by VC measurement. The decrease of VC permit only a suspicion of restrictive defect which must be very often verified by the TLC detecting during plethysmography testing.

STATIC LUNG VOLUMES: VC, FRC, RV, TLC.

Vital capacity (VC) is equal the volume change at the mouth between of full inspiration and complete expiration. The measurement may be made in one of the following manner:

Inspiratory vital capacity (IVC) — the measurement is performed in a relaxed manner, from a position of full expiration to **full inspiration**. This technique gives the best information about the value of VC.

Expiratory vital capacity (EVC) — the measurement is performed from a position of full inspiration to **full expiration**. This technique is very often used but sometime the results are unsatisfactory, especially in obstructive patients.

The **forced vital capacity** (FVC) is very often obtained during the registration of maximal expiratory flow-volume loop. The FVC represents the volume of gas, which is maximal exhaled during a forced expiration, starting from a position of full inspiration. It is important to note that in healthy subjects differences between IVC and FVC or EVC are minimal. But in patients with airflow limitation the relaxed or slow expiratory vital capacity (EVC or SVC) and particularly the forced vital capacity (FVC) can be considerable less than IVC. As a consequence the evaluation of restrictive defect on the basis of FVC is limited. On the other side the calculation of FEV₁ %VC ratio can be overestimated.

DIAGNOSIS OF THE RESTRICTIVE VENTILATORY DEFECT

As it was pointed out above the decrease of VC or FVC is only first sign about a restrictive ventilatory defect. Confirmation of this type of ventilatory defect is necessary. It is important to know if the decrease of vital capacity is reversible or not.

In this aim we have to perform bronchodilatory test — a second spirometry about 15 min after the inhalation. An increase of 15 % FVC (in relation to the first spirometry) after a bronchodilator inhalation is a sign that the reduction of FVC has a functional mechanisms connected with airway obstruction. This functional type of FVC decrease we can often seen in patients with bronchial asthma or sometimes in patients with COPD.

Second procedure is measuring of FRC in body plethysmograph. Especially in emphysema the reduction of FVC is often a secondary effect of over inflation of the lung, which cause an increase of FRC and RV. In patients with emphysema the decrease of VC in spite of increase of TLC is a result of increased FRC.

Only in interstitial lung diseases especially in lung fibrosis the FRC is often reduced as a consequence of reduction of lung parenchyma.

Classification of VC restriction : small — between 75 % and 60 % of pred. VC ; medium — between 60 % and 50 % of pred. and advanced between 50 and 30 % of pred. VC [1].

FUNCTIONAL RESIDUAL CAPACITY (FRC)

It is important to underline that the analysis of FRC (TGV) or RV and total lung capacity (TLC) are very important in the diagno-

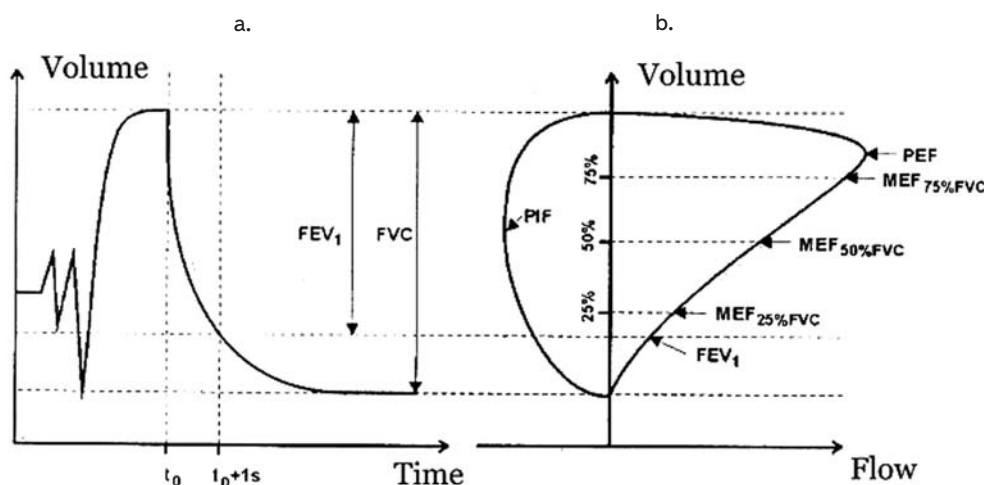


Fig. 1. Spirometric registration in convention volume - time (a), and in convention volume - flow (b). /Pneumonol. Alergol. Pol. 2004, 72:7-9. /

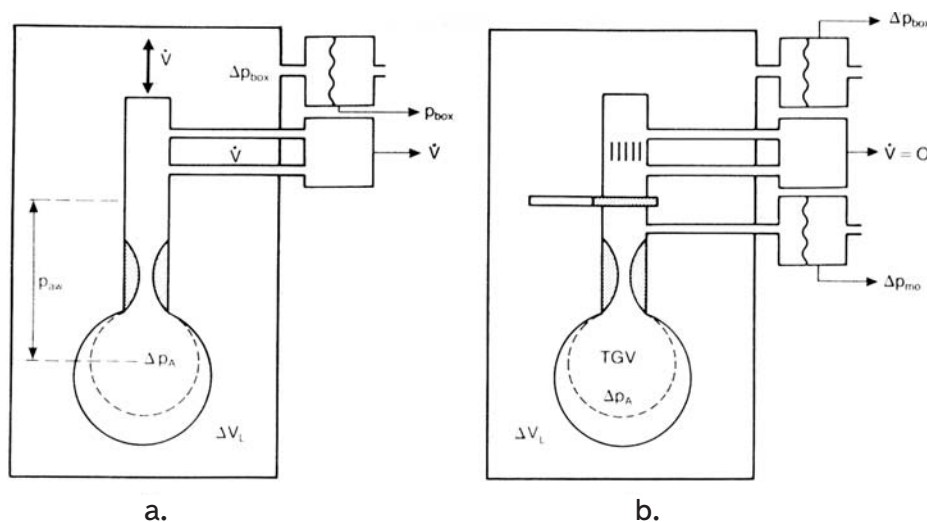


Fig. 2. Schematic presentation of airway resistance (a) and FRC — measurement by whole body plethysmography. Details see text.

sis of lung mechanic disturbances. This analysis requires a body-plethysmograph measurement.

Functional residual capacity (FRC) is the volume of gas remaining in the lung and airways at the end of quiet average expiration. FRC is the volume of the lungs during a normal expiration, when there is no muscle activity and no pressure difference between alveoli and atmosphere. In this position of thorax the equilibrium is attained when the elastic recoil of the lung is exactly balanced by the elastic recoil of the thoracic cage.

After a complete exhaling, air is still in the lung. This remaining volume is the residual volume (RV). It is calculated by subtracting the expiratory reserve volume from the functional residual capacity: $RV = FRC - ERV$.

Total lung capacity (TLC) is the volume of gas in the lung at the end of a full inspiration. $TLC = RV + IVC$. In healthy young adults, FRC is about 50 % of total lung capacity.

In patients with COPD and with predominant signs of emphysema or in advanced bronchial asthma the FRC is often markedly increased ($FRC > 120\%$ pred.). The reason of this hyperinflation of the lung is the decrease of lung elastic recoil as a consequence of the alteration of elastic fibers during irreversible destruction of parenchyma. As a result an alteration of the position of the PV curves of the lungs and chest wall occurs. In this situation the balance of against directed forces occurs at a larger lung volume. In contrary lung overdistention in asthma patients is reversible as a consequence of reduction of airway obstruction.

Clinical results of lung hyperinflation can be enormous such distortions of chest wall motion, impaired inspiratory muscle func-

tion, increased oxygen cost of breathing, hypoventilation with hypercapnia, and greater severity of breathlessness.

MEASUREMENT OF FRC BY WHOLE BODY PLETHYSMOGRAPH (Fig. 2b)

The method is based on Boyle's-Mariotte law, which states that the volume of a fixed quantity of gas at constant temperature varies inversely with the pressure [7, 15]:

$$P \times V = (V + \Delta V) \times (P - \Delta P);$$

If $\Delta P \times \Delta V$ is ignored, and Boyle's — Mariott law is applied to the lung, it states that

$V_L = \Delta P_A \times (\Delta V_L / \Delta P_A)$. Where V_L = lung volume, and P_A = alveolar pressure.

The change in lung volume can be measured indirectly in a volume-constant plethysmograph as a change in box pressure. Changes in mouth pressure should be recorded in phase with changes of pressure in the body box.

Procedure: if the subject sitting in the body box is asked to make respiratory efforts against a closed shutter, variations in TGV due to compression and expansion of gas can be detected by a sensitive manometer. The change in pulmonary gas pressure can be measured at the mouth with an appropriate manometer, since mouth pressure equals alveolar pressure if there is no gas flow. Thoracic gas volume is calculated from the change in alveolar pressure and the concomitant change in box pressure by according to presented Boyle's-Mariott law.

DYNAMIC LUNG VOLUMES: FEV_1 , $FEV_1\%$ pred., $FEV_1\%$ VC [2, 9, 10].

Tiffeneau was the first physician who in the year 1947 intro-

duced the measurement of airway obstruction with forced expiratory volume in one second (FEV_1). FEV_1 presents the volume, which is expired during one second of a maximal expiration after a maximal inspiration. The FEV_1 is the most reproducible, most commonly obtained and most useful measurement to identification of airway obstruction in sense of limitation of maximal expiratory flow. The decrease of FEV_1 reflects the narrowing of the airways as a consequence of inflammation of the bronchial mucous with contemporary broncho-spasmus (asthma) and also in patients with reduction of static elastic recoil pressure (emphysema). The FEV_1 is decreased in different degree, which reflects the severity of the disease. Predicted values of FEV_1 are based on age, gender, height and ethnic characteristics. According the ERS — guidelines it is recommended to use the highest value of FEV_1 from the first three technically satisfactory attempts. The start of forced expiration is obtained by linear extrapolation of the steepest part of the volume-time curve.

Because the decrease of FEV_1 is observed in airway obstruction as the diminution of VC it is recommended to use for the analysis of airway obstruction the FEV_1/VC -ratio or alternatively FEV_1/FVC ratio. The FEV_1/VC ratio is the most sensitive parameter for estimation of airflow limitation. The FEV_1/FVC ratio is generally expressed as a percentage. According the ERS- statements [2] the lower limit of predicted value is 70 % although it does fall with increasing age. According N B Pride from Imperial College School of Medicine [10] in normal adult, the FEV_1/VC ratio ranges from 70 to 75 %.

It is important to point out that the significance of this ratio depends not only from the numerator (FEV_1) but also on the denominator (VC or FVC). During maximal expiratory flow-volume measurements the force vital capacity (FVC) is measured. In patients with clinical stable asthma but with bronchial hyperreactivity the FVC can be reduced and so the $FEV_1\%FVC$ ratio can be over estimation. It is important to know that during repeated measurements the results will be only correct with the same FEV_1 ratio index (FEV_1/VC or FEV_1/FVC). For initial assessment, it is useful to measure the $FEV_1\%VC$ or $FEV_1\%FVC$ ratio. For follow-up of airways obstruction the change in $FEV_1\%pred$ provides more reliable information. Classification of airway obstruction [1, 2, 3, 4] presented on the table.

BRONCHODILATORY TEST

We distinguish two types of obstructive ventilatory failure: dynamic and static. To identification of the mechanisms of airway obstruction very useful is the bronchodilatory test (second spirometry 15 min after inhalation of salbutamol). The increase of 15 % of FEV_1 and 200 ml lung volume during the second spirometric examination is a confirmation that the airway obstruction is responsible and functional. An positive bronchodilatory test is very characteristic for bronchial asthma. In contrary in COPD patients the bronchodilatory effect is seldom pronounced.

3.0 MAXIMAL EXPIRATORY FLOW-VOLUME LOOP (MEF_{50} , MEF_{25} , PEF)

Maximal expiratory flow-volume loop are commonly used as an additional important information source to spirometric data. The flow-volume loop is a graphic analysis of the flow generated

during the FVC maneuver, plotted against volume change. It is usually followed by a deep expiration and forced inspiratory volume (IVC). Flow is usually recorded in liters per second and the volume in liters. The maximal expiratory flow-volume loop is the expiratory part of the curve from TLC to RV. The first part (1/4) of the maximal expiratory curve is largely dependent of the expiratory muscle effort, but the second part of this curve (3) is effort independent. Flow in this segment is determined by the lung elastic recoil and flow resistance.

In bronchial asthma and chronic bronchitis with the domination of the inflammation of the bronchial mucous and secondary bronchospasm this will cause the decrease of maximal expiratory flow. In emphysema the reduction of static elastic recoil pressure will be predominantly responsible for the maximal expiratory flow limitation.

When the $FEV_1\%VC$ is relatively well preserved in same patients we can find reduction of maximal flows in the peripheral part of the airways. Lung functional tests performed by Radwan and Kazimierzczak [12] in patients in clinical stable bronchial asthma with a normal spirogram showed in 60 % of these patients reduced MEF_{50} ($< 60\% pred$). A decrease of the maximal expiratory flow (MEF_{50}) is often interpreted as a sign of airway obstruction especially in small airways.

In the monitoring of airflow values during treatment of asthmatic patients the measurement of peak expiratory flow is helpful. A diurnal variations of PEF more than 20 percents indicated exacerbation of the diseases. But this sign is not specific because it is seen not only in asthma or bronchitis but also in smokers and after viral infections (rhinitis).

4.0 AIRWAY RESISTANCE (R_{aw})

To measure airway resistance we have to estimate the pressure required to produce a flow of 1 L/s in the airways during inspiration and expiration. ($R_{aw} = \Delta P/F$). Persistent driving pressure (ΔP) is the pressure difference between the ends of the tube (alveolar volume-mouth). In healthy adults average R_{aw} is about 1–3,5 cm H₂O/L*s⁻¹

(0,35 kPa/L*s⁻¹). Airway resistance varies inversely with lung volume. At high lung volumes the airways are wider and the resistance is lower. Typically the airway resistance is measured during quiet breathing at functional residual capacity (FRC). In bronchial asthma the increase of R_{aw} is consequence of airways mucous inflammation, bronchospasm and secrete deposition in the airways. In COPD with predominant emphysema R_{aw} is also increased but as a result of mucous inflammation and decline of the lumen of small airways as a consequences of the instability of the airways wall.

There is a strong negative correlation between airway resistance and maximal expiratory flow. Usually a high airway resistance is associated with decreased maximal expiratory flows ($MEFR$) and evidenced by decrease in the force expiratory volume in one second (FEV_1) and $FEV_1\%VC$ ratio. However there are a few exceptions depending on the different mechanisms of airways obstruction and property of methods of measurement (spirometry — forced expiration, body box — quiet breathing). In COPD patients with predominant emphysema and instability of airways wall during a forced expiration maneuver the decrease of FEV_1 can be intensi-

Table

DEGREES OF AIRWAY OBSTRUCTION SPIROMETRIC CRITERIA

DEGREES OF AIRWAY OBSTRUCTION	SPIROMETRIC CRITERIA	
FIRST DEGREE — MILD	$FEV_1\%FVC < 70\%$	$FEV_1 > 80\% pred$
SECOND DEGREE — MODERATE	$FEV_1\%FVC < 70\%$	$50\% pred < FEV_1 < 80\% pred$
THIRD DEGREE — MIDDLE ADVANCED	$FEV_1\%FVC < 70\%$	$30\% pred < FEV_1 < 50\% pred$
FOURTH DEGREE — STRONG ADVANCED	$FEV_1\%FVC < 70\%$	$FEV_1 < 30\% pred$

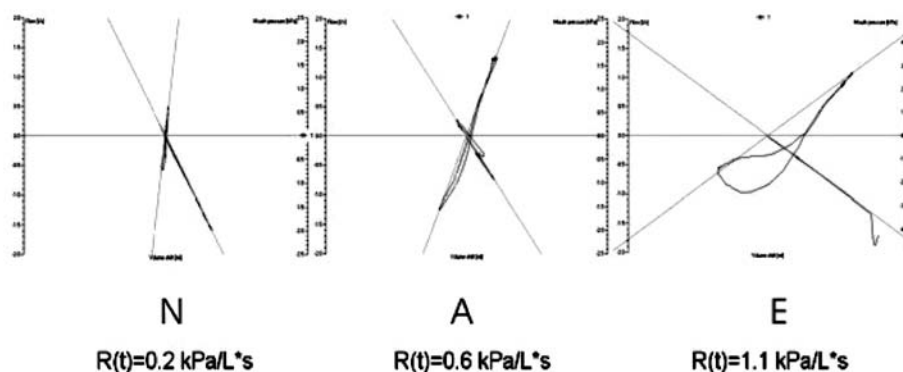


Fig. 3. Differentiations of $Palv/V^\circ$ curve: in healthy subjects (N), in bronchial asthma (A) and in COPD patients. Curve A demonstrates increase of airway resistance without magnificent disturbances of gas distribution (homogenous) during inspiration. Curve B demonstrates great gas distribution disturbances (non-homogenous curve) during ventilation and a characteristic increase of airway resistance in the expiratory phase of respiration as a consequence of instability of the airways wall caused by decrease of lung elasticity [12].

fy by the increase of intrapleural pressure. During R_{aw} measurement the patient breathes without thorax compression with normal intrapleural pressure oscillation. In these circumstances the R_{aw} is only slightly increased [11].

The graphic shape of the resistance curve ($Palv/V^\circ$) contains important information about the different mechanisms of the increase of airway resistance. Homogenous curve is typical for bronchial asthma and non-homogenous curve is more frequent in patients with COPD (Fig. 3).

Repeated simultaneous TGV and R_{aw} measurement and the estimation of R_{aw}/TGV — Index is an useful differential procedure to detection different clinical type of COPD (Pink puffer and Blou bloater (Fig. 4).

It has been suggested that R_{aw} is electively sensitive to changes in the central airways, while the MEFR, especially when measured at low lung volumes, is influenced to a larger extent by the caliber of peripheral airways (< 2 mm) [13]. The resistance of the peripheral airways, including the small airways and parenchyma, has been measured directly in humans using a variation of the retrograde catheter technique. Using this technique Wagner et al. [16] showed that in asthmatics with normal spirometry, the peripheral resistance (R_p) was increased up to seven-fold as compared to control subjects.

AIRWAY RESISTANCE MEASUREMENT BY BODY PLETHYSMOGRAPHY (Fig. 2b.)

The most commonly method of measuring R_{aw} is the plethysmographic technique of DuBois, Botelho and Comroe [8]. The subject, usually is sitting in a constant volume plethysmograph, breathes through a pneumotachograph and measurements of flow and box pressure (P_{box}) are displayed on x — y recorder and the angle $\Delta P_{box}/\Delta V^\circ$ is measured. The shutter is than closed to allow the calibration of the P_{box} signal in terms of $Palv$.

Multiplication of third slopes of these two relationships gives airways resistance: $R_{aw} = \Delta Palv/\Delta V^\circ$.

5.0. STATIC LUNG COMPLIANCE (C_{st}).

During inspiration the respiratory muscles must overcome both the resistance of the flow in the airways and the elastic recoil of the tissues. The elastic recoil of the lungs is opposed by the elasticity of the chest wall. This creates a sub-atmospheric pressure in the intrapleural space. The final point of "balance of the lung and chest wall" combination is the resting expiratory level, which determinates the functional residual capacity (FRC).

The elastic recoil of the lung is produced by two components of approximately equal magnitude. These are the elastic feature of the lung tissue itself and surface tension of the fluid lining the alveoli.

The elastic recoil of the lung is given by the ratio volume change in relation to the change in transpulmonary pressure measured in the esophagus with a catheter. (Compliance $C_{st} = V/P$). In healthy subjects the increase of the lungs about 250 ml needs a pressure difference of about 1cm H_2O . In all diseases which lead to

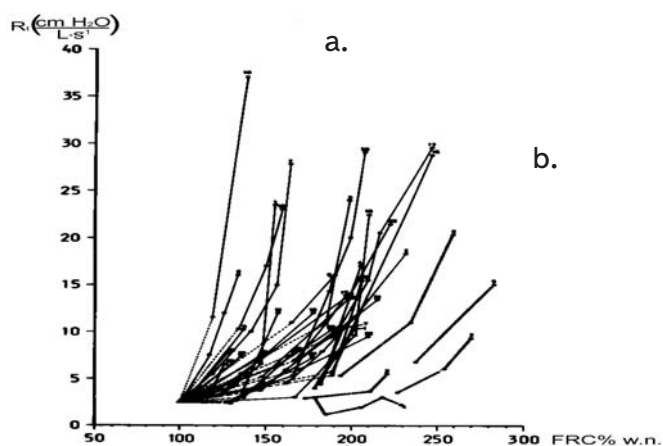


Fig. 4. R_{aw}/TGV index can be very useful in the differentiation procedure of COPD patients in two clinical groups: pink puffer (a) and blou bloater (b). Type a is characterized by increase of airway resistance without overdystention of the lung. Type b is characterized by great lung overdystention but only with decent increase of the airway resistance.

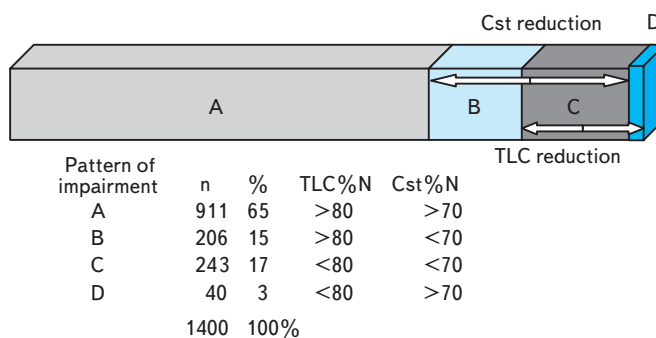


Fig. 5. Results of analysis of lung mechanics parameter in 1400 patients with interstitial lung diseases (sarcoidosis, lung fibrosis, alveolitis allergica and with diverse clinical status). Restrictive ventilatory defect (TLC < 70 % was found only in 20 % of patients with interstitial lung diseases). In contrary the reduction of lung compliance (C_{st}) was in 32 % of patients manifest. We conclude that the reduction of C_{st} is a very sensitive sign of pathology process in the lung parenchyma [6].

a fibrosis transformation of the lungs the increase of stiffness is observed. This means that elasticity is growing but the compliance of the lung will be reduced. Generally there is a good correlation ship between the reduction of the compliance and the restriction of

the lung volume in these patients. But it is important to note that very often in patients with interstitial lung diseases we find primarily the reduction of Cst in relation to lung volume restriction. In the last year a retrospective cross-sectional analysis of pulmonary function data (spirometry, whole body plethysmography) in the Department of Physiopathology of the Institute of Lung Diseases in Warsaw was performed [6]. Investigation in 1400 patients with interstitial lung diseases showed very interesting results. In these patients this analysis showed a reduction of total lung capacity (TLC < 80 %) only in 20 % of the studied patients. In contrary to the TLC the reduction of the compliance (C_{st} < 70 %) was reduced in 32 % of all examined patients. The conclusion of this study is that in many patients with interstitial lung diseases the decrease of lung compliance is the most sensitive sign of the fibrosis transformation of the lung. We represent the opinion that in early diagnosis of the interstitial lung diseases measurement of lung compliance is indicated.

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