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THE SPIROMETERS TESTING

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Abstract: The spirometer is a measuring instrument which should give information about some mechanical parameters of the respiratory system in a synonymous and precise means. It consists of two main blocks: 1- the spirometric transducer, which converts non electric value, usually gas flow, into electric signal, 2- the electronic block, which measures, converts and presents the results. Their metrological parameters are usually tested by using a calibrating syringe, forced vital capacity simulator or standard waveforms gathered on a diskette. In this article the author proposes a new method of spirometer testing: two spirometers, i.e. the tested one and the standard one are serially connected into a course of calibrating signals. In this way the user can obtain quick information about tested instrument quality.

Keywords: spirometry, spirometer testing.

1 INTRODUCTION

The spirometer is an instrument, which should give the user complete information about some mechanical features of the respiratory system - in a precise way. The producer usually proposes the kind of measured values which will be measured precisely. Almost all metrological parameters are defined in a steady state and static conditions, which are far from reality. There are: pneumotachometers characteristics and its flow resistance. For this reason many instruments, even with similar technical parameters, can give for the same patient, extremely different results. To avoid such situations some calibrating procedures are realised, which allow us to compare measuring results obtained from different spirometers.

2 FUNDAMENTAL SPIROMETER BLOCKS AND THEIR FUNCTIONS

Each spirometer consists of two fundamental blocks (Fig. 1):

1. non-electrical value sensor (of volume or flow velocity) co-operating with the transducer, with electrical signal on its output (voltage, pulses),
2. a block of processing electrical information and presenting the final results.

Figure 1. General block diagram of electronic spirometer. P – pneumotachometer (Fleish head)j, BEP - block of electrical processing, AAD amplifier and A/D converter, MCS - microcomputer with software, BFRP - block of final results presentation.

All these blocks decide final preciseness of the spirometer. For this reason testing them is so important. The most popular spirometric transducer is a pneumotachometric Fleish head. It realises flow velocity conversion into pressure differences and then into voltage (Fig. 2).

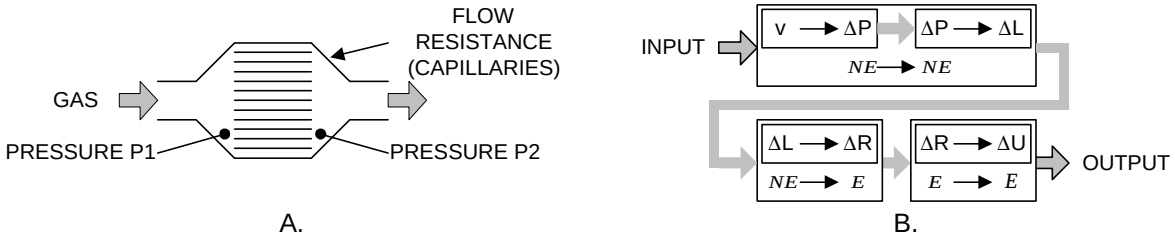

Figure 2. The general scheme of pneumotachometric head (A) and steps of signal conversion (B) (NE - non electric value, E - electric value; v - flow velocity, P - pressure, L - membrane deflection, R - resistance, U - voltage).

The block of electrical processing must amplify the electric signal obtained from the pneumotachometer and match it into input signal level of A/D converter. A microcomputer with software, making many mathematical calculations, realises some tasks:

1. identification of the spirogram V(t) beginning,
2. correction all data, taking into consideration pneumotachometes ninlinearities,
3. discrete integration/differentiation of the signal,
4. finding signal samples needed for spirometric parameters calculation,
5. correction of the results with physical conditions (e.g. ambient temperature),
6. comparison of measured spirometric parameters with predicted (normal) values,
7. final results storage and presentation in the form of digital data and diagrams.

3 CHECKING OF THE PNEUMOTACHOMETER ACCURACY

The pneumotachometric head plays a fundamental role in signal reception from the medical object through its converting accuracy (gas flow velocity into voltage conversion), characteristic nonlinearity and its flow resistance. The head characteristic is checked in static conditions. This means that when only flow remains constant output signal (usually voltage value) answers at a constant level. In practice this answer is frequently nonlinear. Figure 3 presents curvilinear pneumotachometric head characteristic, which can be software corrected, giving linearization effect. At the beginning this characteristic had the form: $v = -2.76E\text{-}07U^2 + 4.35E\text{-}03U + 1.7E\text{-}01$. For this linearization some coefficients of this formulae must be taken into account. This decreased nonlinearity error from level 2.7 % to 1.2 %, diminishing the final error in this way.

Figure 3. An example of pneumotachometric head characteristic (A) G02 connected with ΔP/U transducer type MOTOROLA MPX12D. The effect of characteristic linearization (B) of the same head is the source of error.

Head flow resistance takes the main role in checking the signal from the medical object. It must be very high (R_z), because head sensitivity should be high, according to the formulae:

$$U = K \Delta P = R_z v \qquad (1)$$

where: U - head voltage answer, K - conversion constant, ΔP - pressure difference like answer of gas flow v. On the other hand it should be minimal; the resistance R_g which is noticed is the sum of reducing pipe resistance R_z and tube resistance R_p, which connects the patient with the pneumotachometer: $R_g = R_z + R_p$. This resistance is serially connected with lung flow resistance (Fig. 4).

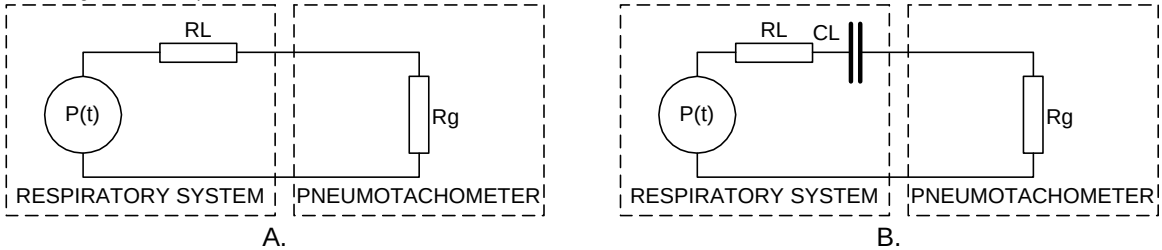

Figure 4. The diagram illustrating the role of spirometer resistance R_g in flow observation (A). This is analogue to the electric circuit. Theoretically, in steady state, flow velocity is defined like $v_t = P/R_L$. Whilst connecting the instrument with resistance R_g the flow diminishes and then $v_r = P/(R_L + R_g)$. The model for respiratory system in forced expiration[1] is presented in figure (B).

[1] Forced expiration is the fundamental spirometric test: the patient inhales maximal gas volume into his lungs and then exhales it with maximal force and velocity.

In this way flow v_i diminishes into v_r value. During forced expiration this extra head resistance will change lung time constant (compare: Fig. 4B).
According to electric analogue such measuring device resistance brings about the method error (analogue: the method error in current measurement) and can be eliminated with using the correction factor. But in spirometrical practice this way is not used. Rather it is better to agree with such an error, but only when it is very little. For this reason it is suggested the spirometer resistance R_g ought be not bigger than 1.5 cm H_2O/l/s for flow velocity v = 12 l/s [1].
But an extra non-measured reaction which exists between lung and instrument must be taken into account. Here appears such a phenomenon: during forced expiration for overcoming transducer resistance the patient must generate a higher (than normal) pressure in his lungs. This pressure is bigger if the spirometer resistance is bigger. This higher pressure appearing in the lungs opens usually blocked (especially in pathology) respiratory ducts and in result extra gas volume flows out, which normally (during normal breathing) does not exist. Then, expired volume is abnormally higher, which means that the measured results are doubtful. It is very difficult to define the value of this error. Therefore the results obtained from different spirometers, with different resistance R_g can be discordant.

4 THE TEST OF ELECTRIC CONVERSION BLOCK

The procedures of pneumotachometric signal conversion are dictated not only by head technical parameters but especially by medical object features. During forced expiration the volume changes exponentially. This change of velocity tells us about the state of the respiratory ducts (resistance R_L) and of the alveoli (compliance C_L) (compare Fig. 5).

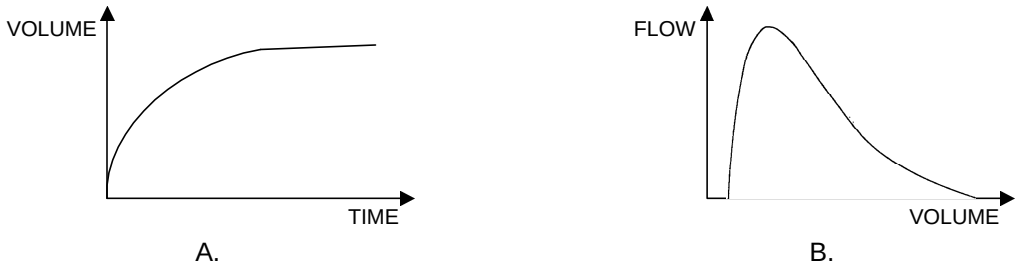

Figure 5. Forced expiratory curve called TVC (timed vital capacity curve) (A). It presents expired volume changes in time: $V(t) = V_o (1 - e^{-t/(RL\ CL)})$. The part of the respiratory loop called MEFV (maximal expiratory flow-volume curve) (B) presents only forced expiration: FEF_{max} is the maximal value of flow velocity observed during forced expiration.

On the basis of this test there different spirometric parameters are defined [2] which can be divided into three categories:

1. gas volumes (e.g. forced vital capacity FVC),
2. mean values of gas flow velocities (e.g. forced expiratory volume expired during the first second of forced expiration FEV_1),
3. instantaneous values of gas flow velocities (e.g. maximal forced expiratory flow FEF_{max}).

The procedures of defining all these parameters are realised by easy arithmetic calculations with using signal samples $V(t_i)$ or $v(t_i)$. But most essential is to catch the starting moment of forced expiration. Not precisely established moment $t_o = 0$ can be an essential source of error for all these calculations, where the time is taken into account. Perceptible time delay at the very beginning of the forced expiration signal V(t) is the result of the influence on the inertia system of both the patient and the pneumotachometer. For elimination such flow special extrapolation procedures are used which can help to define the synonymous signal of the starting moment (Fig. 6)

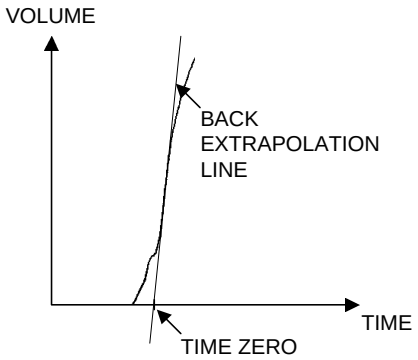

Figure 6. The typical spirogram form V(t) and extrapolation of the zero-point (starting point) [3].

Software testing, especially for calculation procedures, are realised by using special data which are stored on diskette (Fig. 7).

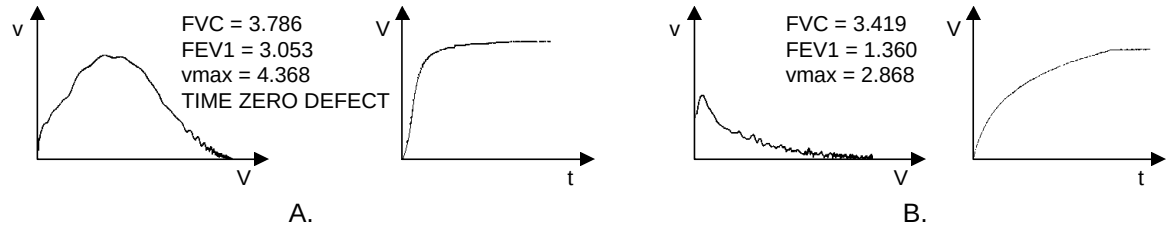

Figure 7. Some examples of testing spirometric curves no 14 (A) and no 23 (B) [3].

5 THE REAL CONDITIONS OF SPIROMETER TESTING

Both pneumotachometric head and electronic blocks decide about the spirometer preciseness. For this reason they should be tested together. In practice some testing methods are known.

5.1 One-point-direct testing method

This direct testing is realised by using the respiratory system simulator. Usually it is a calibrating volume-constant syringe with stiff walls and output (orifice) in the form of a stiff tube. The gas flow depends on the direction of piston movement, about which the user decides. Such syringes are standard equipment of every spirometer. Typical volume is one or three litters, with preciseness better then 3 %. The user tests the spirometer himself. This way of testing can be called „one-point", because only one precise value of volume is obtained [4]. Such a test is especially useful for quick definition of constant K for the spirometer, in accordance with the relation: 1 litre = K · spirometer reading.

5.2 Many-points- direct testing method

In this way the spirometer can be tested in some points: for different volumes and flow velocities [5]. The signal most similar to the reality generates the forced vital capacity simulator. Volume changes agree with the formulae:

$$V(t) = V_s \left(1 - e^{-t/\tau_S}\right) \qquad (2)$$

where: V_s - the maximum volume, τ_s - time constant of the generated signal.
For such a form of testing signal it is easy to calculate all values of simulated spirometric parameters. This method realises the forced expiration simulator [6] or calibrator with special cartridge [7]. To be sure, it is easy to test read-out of some spirometers but is impossible to investigate pneumotachometer in the full range of working.

5.3 Indirect testing method

The spirometer can also be tested by using a group of patients [8]. They are measured independently, in succession, on every instrument. This method was used to test two devices: S-Model (Vitalograph) and Stolberg (Zimmerman) (Fig. 7).

Figure 8. The results of the comparison of the two spirometers: S-Model (Vitalograph) and Stolberg (Zimmerman). The analysis was made for two parameters: FEV_1 (A) and FVC (B) in a group of 21 patients. In this way we can notice, that S-Model usually gives higher values of both parameters (+0.60 l for FEV_1 and + 0.53 l for FVC).

Although both instruments co-operated with real medical object - the patient, if the pneumotachometers have different resistance the differences in value of spirometric parameters can lead to faulty conclusions.

6 CONCURRENT SPIROMETER TESTING

It was noticed, that the pneumotachometric head is serially connected into a measured circuit (compare Fig. 4) which is an analogy to current measurement in electric circuit with using an ammeter. One of the methods in ammeters testing is to connect them serially into a current circuit. In this way current source resistance can be neglected during analysis and for this reason both ammeters should give the observer the same read-out.
Analogously: spirometric results obtained form different instruments, serially connected, should be the same (in margin of measuring error). The source of testing signal can be generated both from the simulator or from the patient (or group of patients).

6.1 Test with using calibrating syringe

A syringe with a volume of one litre (accuracy 1 %) was used for this test. The method of its connection into the tested spirometers is presented in Fig. 8.

Figure 8. Serially connected pneumotachometric heads and calibrating syringe.

The standard instrument was a spirometer Vitalograph Compact II. Because the volume changes were unrepeatable (the piston was moved by hand) only the final volume of one litre was controlled (see Tab. 1).

Table 1. The results of checking K constant for the spirometers serially connected with the standard (only in couples: standard + one tested spirometer). The number of tests n = 20.

kind of spirometer									
Vitalograph Compact II		G02		G04		G05		G07	
mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
1.004	0.005	1.895	0.031	3.138	0.512	1.301	0.084	0.643	0.071

6.2 Tests made during patients measurements

The spirometers were tested in couples as in p. 6.1. Two spirometric parameters were controlled: FEV_1 and FVC (Tab. 2), each of them 20 times. Before taking measurements, the devices were calibrated, for definition K constant, in 10 trials.

Table 2. The results of testing of four spirometers: G02, G04, G05, G07. Standard spirometer: Vitalograph Compact II.

kind of spirometer	FEV_1			FVC		
	K_{FEV1} mean	dispersion [%]	correlation coefficient	K_{FVC} mean	dispersion [%]	correlation coefficient
G02	1.220	30.2	0.93	1.214	36.8	0.83
G04	3.406	25.5	0.96	4.269	44.2	0.56
G05	1.375	12.6	0.79	1.661	14.2	0.74
G07	0.716	24.7	0.97	0.795	11.6	0.94

K constant for each spirometer was defined in three ways:
1. with using calibrated syringe (K constant),
2. in comparison with a standard spirometer, for parameter FEV_1 (K_{FEV1} constant),
3. in comparison with a standard spirometer, for parameter FVC (K_{FVC} constant).

6.3 Results

The suggested method of concurrent spirometers testing gives quick information about reliability of measurement results in devices particularly new for the user.
The differences which appear in K constant (K_{FEV1}, K_{FVC}) can prove nonlinearities in the pneumotachometric heads, which probably were not taken into consideration in software procedures. They suggest that it would be better at first to test these characteristics and then the flow resistance.
Probably different values of K, K_{FEV1}, K_{FVC} constant may also be the result of great flow resistance (summarised resistance of connected pneumotachometers).

7 CONCLUSIONS

Each spirometer is built of two extremely different blocks:
1. mechanical - pneumotachometer head,
2. electrical - block of analogic and discrete conversion.

For this reason the procedure of its test can concern either mechanical or electrical part, or both of them simultaneously.
Popularly used calibrating constant volume syringes can give information about one point only. It isn't possible to test an instrument to its full range. Such manner is useful only for a quick test of spirometer readings readiness. The testing signal collection proposed in [3] is destined only for software, excluding the pneumotachometric head.
With regard to head flow resistance, which co-operates with the respiratory resistance, concurrent tests with serially connected spirometers can give complete information in full range.

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