XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

ABOUT SOME METROLOGICAL ASPECTS OF STANDARDIZATION IN SPIROMETRY

Barbara JUROSZEK

Wroclaw University of Technology, Wroclaw, Poland, e-mail: barbara@pwr.wroc.pl

Abstract: Almost all of the spirometric parameters are measured or calculated during forced expiration because it is one of the most popular and most valuable tests. The American Thoracic Society (ATS) together with The European Respiratory Society (ERS) formulated the technical requirements, which should be fulfilled in spirometry today. The author shows how these requirements can be fulfilled in modern digital spirometers.

Keywords: forced expiration, digitalization, measuring errors.

1. INTRODUCTION

One of the methods of respiratory system testing is the control of their mechanics operation. For this reason air volume filling the lungs and air flow velocity going into/out of the lungs is measured. The correct identification of the lungs features strong depends on the quality of the testing instrument, that registers the output signal (the air volume $V(t)$ or the air flow velocity $Q(t)$). The technical requirements concerning the measuring accuracy were published by The American Thoracic Society in e.g. [1]. The metrological requirements are presented in the short form in Table 1.

Table 1. Minimal recommendations for spirometry accuracy [1]

Parameter	Accuracy*	
FVC	3 % or 0.05 dm^3	*whichever is greater
FEV_1	3 % or 0.05 dm^3	
$MMEF_{25\%\text{-}75\%FVC}$	5 % or 0.20 dm^3/s	

Nowadays all spirometric measurements are made by digital method (data is presented in discrete form) and that is why their preciseness can be better than with old instruments. It means, that the recommendations presented in [1] and concerning final accuracy should be revised. Especially it concerns the signal's digital conversion. Its better accuracy means that the other errors whose source is the spirometric transducer's resistance influence and the air's physical features need to be revised too. All these error components decided about the measuring accuracy.

2. THE EXPIRATORY PARAMETERS DEFINITION

The pulmonary function tests include flow rates and lungs volumes measurements (Table 2) that are continuously displayed during a very important *forced breathing manoeuvre* (the FVC-test). The main one is Forced Vital Capacity *FVC* – the maximum expired air volume. During all forced expiration the volumes are measured at different moments: 0.5, 0.85, 1, 2, 3 second (Fig. 1.a). The instantaneous values of flows are measured at the moments defined by the part of *FVC* value (Fig. 1.b). A kind of analogy are mean flows (Fig. 1.c). Peak Flow *PF* is the maximum flow that appears at the very beginning of the expiration. The meaning of all abbreviations can be found e.g. in [1]. Figure 1 shows the way of defining different parameters.

Table 2. Four categories of the spirometric parameters

Parameter		Examples
Volumes	General	FVC
	Defined by time	$FEV_{0.5}$ $FEV_{0.85}$ FEV_1 FEV_2 FEV_3
Flows	Instantaneous value	$MEF_{25\%FVC}$ $MEF_{50\%FVC}$ $MEF_{75\%FVC}$ PF
	Mean value	$MMEF_{0\%\text{-}50\%FVC}$ $MMEF_{25\%\text{-}75\%FVC}$, $MMEF_{75\%\text{-}85\%FVC}$ $MMEF_{50\%\text{-}100\%FVC}$

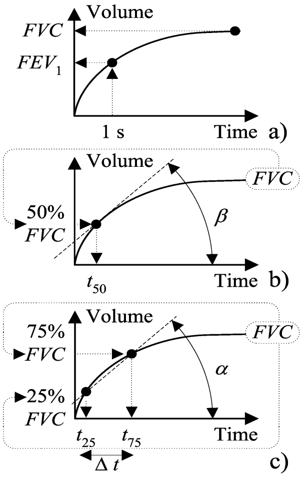

Fig. 1. The way of defining: a) timed volume FEV_1, b) instantaneous flow $MEF_{50\%FVC}$ as tangent with slope α, c) mean flow $MMEF_{25\%\text{-}75\%FVC}$ as secant with slope β

3. THE BASIC LUNGS' MODEL FOR THE ERROR ANALYSIS

The lungs, the main part of the respiratory system, are built of the rigid airways and the elastic alveoli. A model which generally takes the respiratory system features into account, gives the possibility of constructing and choosing the proper device when planning the right measuring methods. The simplest is the electrical model that has the form of a serial *RC* circuit (where *R* is the airway flow resistance, *C* is the alveolar compliance, $\tau = RC$ is the lungs time constant). It is especially useful for the forced expiration analysis. The formulas of the air volume and the air flow rate obtained during forced expiration have the forms [2]:

$$V(t) = FVC\left[1 - \exp\left(-t/\tau\right)\right],\; Q(t) = \frac{d}{dt}V(t) \qquad (1)$$

where *FVC* – Forced Vital Capacity, τ – the lungs time constant.

4. AD CONVERSION

Today all spirometers contain microprocessors and all computational procedures are executed by digital conversion (on the basis of the signal sampling and presentation of each sample in discrete form). This is the reason why the criteria being formulated in [1] as “not numerical” seems to be insufficient.

While choosing a sampling frequency, the basis is the high frequency which doesn’t exceed 12 Hz for FVC-curve. For obtaining proper accuracy the authors of some reports (e.g. [3, 4]) advise sampling with a frequency of 100 Hz, 250 Hz or higher, and using an AD converter 10– or 12–bits (comp. Table 3).

Table 3. Minimal flow identified in AD converter with different resolution

n [bit]	8	10	12	14	16
Δ_r [dm^3/s]	0.04	0.01	0.002	0.0006	0.0002
δ_r [%]	4	1	0.2	0.06	0.02

n – AD converter’s resolution; Δ_r calculated for the maximum flow 10 dm^3/s; δ_r – the relative error calculated for the flow Q = 1 dm^3/s

Because FVC-curve characterises an unrepeatable phenomenon, without possibilities of repeating it with satisfactory precision (because of the existing so called *biological changeability*), all the expiratory parameters in the FVC-test are defined just after its reconstruction, i.e. when Forced Expiratory Volume *FVC* is measured (comp. Fig. 1). The expiratory curve is restored on the basis of the samples collection. Such an obtained signal is presented with a precision dependent on the sampling frequency, the AD converter’s resolution and the way of its approximation between the samples.

The expiratory curve is registered the most frequently in a form of flow $Q(t)$. This signal, sampled in time, can be reconstructed between the samples in two easiest forms: with a step function or a linear one (Fig. 2). The form of reconstruction defines this curve with two errors: for the time and for the flow and in consequence for the volume. Reconstruction when using a step approximating function gives an error of the time and flow defined:

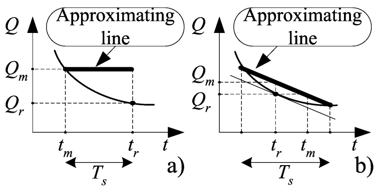

Fig. 2. The way of reconstruction of the curve between two samples: a) with a step function, b) with a linear function; T_s – the sampling period

$$\delta_{S\,t}(t) = -\frac{T_s}{t+T_s}\ ,\ \delta_{S\,Q}(t) = \frac{1-e^{-T_s/\tau}}{e^{-T_s/\tau}} \tag{2}$$

where: t – the flowing time, T_s – the sampling period, τ - the respiratory system time constant. Each flow value Q_i is the basis for the volume V_i calculations as a sum of respective rectangles (Fig. 3). In this case the error has the form:

$$\delta_{S\,V}(n\,T_s) = \frac{T_s \cdot \sum_{i=0}^{n} Q\,(i\,T_s) - V\,[(n+1)\,T_s]}{V\,[(n+1)\,T_s]} \tag{3}$$

where n – the number of a current sample Q_i.

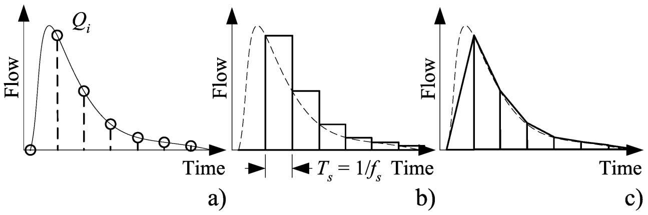

Fig. 3. The conversion of FVC-signal: a) flow $Q(t)$ is presented by the sample value Q_i; b) the volume $V(t)$ as an integral of flow is approximated by the sum of the rectangle areas; c) the volume as a sum of the trapezoid areas

Keeping account in the calculations of the effects of the signal discretization in time, flow and volume errors $\delta_{S\,t}{}^{(d)}$, $\delta_{S\,Q}{}^{(d)}$, $\delta_{S\,V}{}^{(d)}$ have the forms similar to these defined by equations (2) and (3), in which the respective values of $Q_m{}^{(d)}$ and $V_m{}^{(d)}$ (index m means: measured) are:

$$Q_m^{(d)}(i\,T_s) = \frac{FVC}{\tau}\cdot e^{-iT_s/\tau} + \Delta_r,\ V_m^{(d)}(t) = T_s \cdot \sum_{i=0}^{n}[Q(i\,T_s)+\Delta_r] \tag{4}$$

where Δ_r is the AD converter’s resolution for the flow.

Composition of both procedures – sampling and discretization – gives the final error. The theoretical analysis shows that it has nonlinear form (Fig. 4).

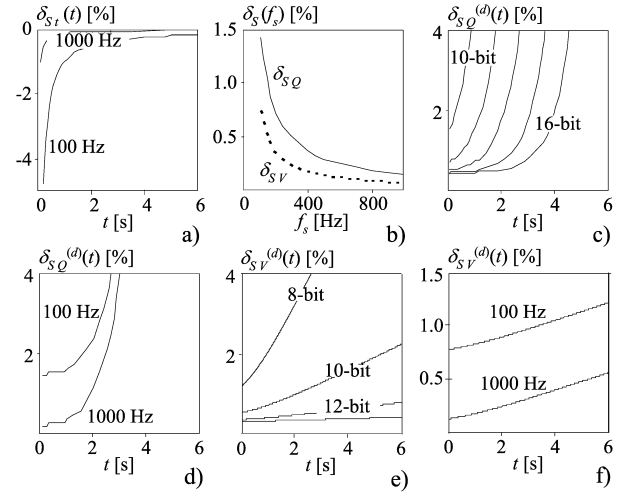

Fig. 4. The errors of FVC-curve reconstruction on the basis of samples collection for different sampling frequencies and different AD converter’s resolution, with step approximation between samples and with discretization error (signed $^{(d)}$): a) time definition, b) the errors $\delta_{S\,Q}$ and $\delta_{S\,V}$ as a function of sampling frequencies, c) $\delta_{S\,Q}{}^{(d)}$ for different AD converter’s resolution when f_s = 250 Hz, d) $\delta_{S\,Q}{}^{(d)}$ for different sampling frequencies, for 12-bit AD converter, e), f) the respective errors calculated for the volume. The calculations presented for signal’s parameters: FVC = 3 dm^3, τ = 0.7 s and 6 s of the expiration [5]

The error $\delta_{S\,t}$ of time definition changes when time of the forced expiration flows (Fig. 4.a). The biggest value appears at the beginning part of the expiration and then dramatically diminishes. When the sampling frequency is 1000 Hz it has a value of less than half percent. It is noticeable that the error for the volume is considerably smaller than for the flow (Fig. 4.b), although the volume is calculated on basis of flow. The reason is the basic function form (see eq. (1)) and the fact, that in the case of volume the absolute error (although it is a sum of absolute errors concerning flow) is referred to increasing value of the volume, while the absolute error of the flow is referred to its decreasing value.

Appearing discretization extends the final error. The errors grow in time, having huge values, particularly in the end part of the flow curve. However such changes are fast for the flow (Fig. 4.c.d) but for the volume they are mild (Fig. 4.e.f). The sampling frequency doesn't change the error much. Finally, the sampling frequency has a small influence whereas AD converter's resolution has the most important influence. It suggests that the AD converter used in spirometry should be 12-bit or better. It means, that a recommended AD transducer better than 12-bit seems to be good enough but sampling frequency f_s = 250 Hz may be rather insufficient.

The above considerations concern the method of step approximation between the signal samples. Linear approximation makes all the errors considerably smaller which confirm the results of simulations. Calculations presented in Fig. 5 differ from the results in Fig. 4.

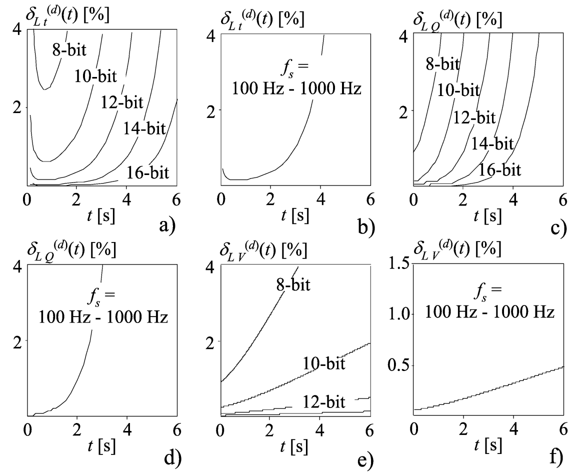

Fig. 5. The errors of the FVC-curve reconstruction on the basis of samples collection for different sampling frequencies and AD converter's resolution, with linear approximation between samples and with discretization error (signed $^{(d)}$): a) $\delta_{L\,t}^{(d)}$ for different AD converter's resolution when f_s = 250 Hz, b) $\delta_{L\,t}^{(d)}$ for different sampling frequencies (the same results for f_s = (100 ÷ 1000) Hz), for 12-bit AD converter, c) $\delta_{L\,Q}^{(d)}$ for different AD converter's resolution when f_s = 250 Hz, d) $\delta_{L\,Q}^{(d)}$ for different sampling frequencies (the same results for f_s = (100 ÷ 1000) Hz), 12-bit AD converter, e), f) the respective errors calculated for the volume. The calculations presented for signal's parameters: *FVC* = 3 dm^3, τ = 0.7 s and 6 s of the expiration

They show that in linear approximation the errors are smaller than in the step approximation and the character of error changes is similar. The errors are bigger at the final part of the forced expiratory curve. The AD converter's resolution has a bigger influence than the sampling frequency. The error being the result of sampling frequency remains almost the same. $V(t)$ curve is reconstructed more correctly than $Q(t)$ curve. In this case a 12-bit AD converter and sampling frequency f_s = 250 Hz, suggested for use in spirometry, seems to be enough.

5. ERRORS IN THE FORCED EXPIRATORY PARAMETERS' DEFINITION

The signal presentation in the form of samples has its consequences in the accuracy of the measured expiratory parameters. The examples are depicted in Fig. 6 where errors for *FEV* and *MEF* parameters have been calculated.

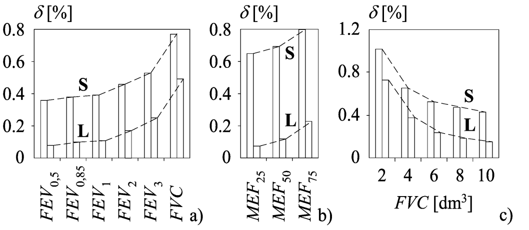

Fig. 6. The errors for different parameters when step (S) and linear (L) approximations are used: a) the volumes *FEV*, b) the flows *MEF*; the calculations were made for f_s = 250 Hz, *n* = 12 bits, for the curve for which is *FVC* = 3 dm^3, τ = 0.7 s, the expiration time 6 s, c) for the curves with different values of *FVC*

These results confirm the earlier simulations. The errors are smaller for the parameters that are calculated at the beginning part of the expiration. Flows (*MEF*s) are defined rather less accurately than volumes (*FEV*s).When to use the linear approximation between the samples the errors for flows become about five times smaller; for volumes – the errors are about two times smaller.

Although the accuracy, being the result of signal sampling, is satisfying in final error we should take into consideration the other components like the flow transducer's accuracy and the expired air's physical conditions.

6. THE INFLUENCE OF AIR PARAMETERS ON THE RESULTS OF A SPIROMETRIC TEST WHEN FLOW TRANSDUCERS ARE USED

Gas filling the lungs is warm and moist, but when exhaled, it changes its physical features. That is why the special coefficient *K* is widely used for needed correction, changing measuring results into real conditions, which are inside the lungs. It has the form:

$$K = \frac{310}{273 + T_a} \cdot \frac{P_a - P_{H_2O}(T_a)}{P_a - 6.26} \qquad (5)$$

where T_a is ambient temperature, in ^{o}C, P_a is ambient pressure, in kPa, $P_{H_2O}(T_a)$ is water vapor pressure of the air in ambient temperature, in kPa.

The ambient temperature has the biggest influence (see Table 4) because it is usually lower then the temperature of expired gas. It decides about water vapor pressure indirectly P_{H_2O}. The ambient pressure can be neglected.

Table 4. The relative values of dispersion of *K* coefficient for different physical conditions, for K_0 = 1.102 (K_0 was calculated for: T_a = +20^{o}C, P_a = 101.3 kPa) [6]

Parameter	Range	Maximal differences [%]	Range of *K* value	Dispersion *K* [%]
T_a [^{o}C]	+(15÷25)	25	1.128÷1.074	2.5
P_{H2O} [kPa]	1.6881÷3.1583	30		
P_a [kPa]	98÷104	3.3	1.103÷1.101	0.1

As was shown in [6] the coefficient *K* must be indispensably used in the volumetric transducers. In the opposite case we have the significant error (Fig. 7).

Nowadays modern instruments use the flow transducers that are the most popular in spirometry. Such a transducer is placed near the mouth and that is why the temperature of expired gas is neither ambient nor +37°C (the patient's). For better accuracy the temperature near the mouth should be measured. Neglecting ambient temperature will give a smaller error than taking its value into consideration. It should be noticed that the form of equation (4) with the value of ambient temperature can be used only for the volumetric transducers.

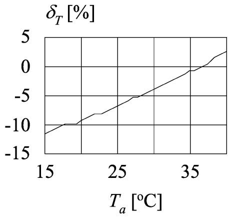

Fig. 7. The error of the ambient temperature T_a influence in spirometry

7. THE ERROR CAUSED BY SPIROMETRIC TRANSDUCER FLOW RESISTANCE

The accuracy of the spirometric measurements obviously depends on the spirometric transducer's quality: its accuracy, linearity, repeatability, long term stability, response time or dynamic answer and flow resistance. Some of its parameters (e.g. linearity, accuracy) we can make better now, when we use *an intelligent* (*smart*) transducer. However, its flow resistance sometimes can change the results. This flow resistance is defined at 12 dm^3/s [7] and its recommended value should be not bigger than 150 Pa·s/dm^3.

During forced expiration R_s changes according to air flow. When the flow is big the resistance is big (Fig. 8). In accordance with equations (1) it changes the picture of the forced expiration which theoretically can be expressed for the new time constant $\tau_F = (R+R_s)\,C$, where R_s is the transducer's flow resistance [8]. In every moment of the forced expiration the amount of expired gas volume $V_s(t)$ is defined with an error $\delta_V(t)$. The differences are biggest at the beginning part of the forced expiration when air flow velocity is maximum and where most parameters are defined [9]. The patients' measurements confirm the theoretical analysis (Fig. 9).

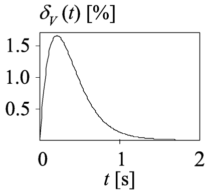

Fig. 8. The error of the volume definition being the result of transducer's flow resistance influence [8]

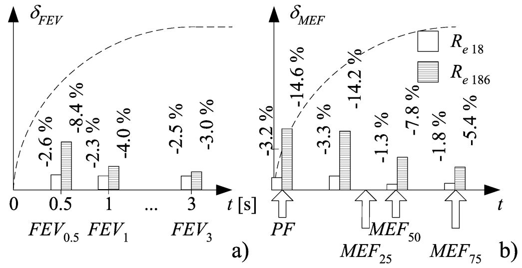

Fig. 9. The expiratory parameters measured with the use of a spirometric transducer having simulated different values of flow resistance. Tested subject: PF = 4.60 dm^3/s, FVC = 3.57 dm^3, FEV_1/FVC = 80%. Extra flow resistors R_e's were serially connected with the original transducer of the spirometer Compact II. The relative differences are presented as percent of expiratory parameters, in the background of FVC-curve $V(t)$. Graphs demonstrate two categories of the parameters: a) volumes, b) flows

The transducer's flow resistance means that the values of the parameters that are defined at the beginning part of the forced expiration can be considerably changed because they concern the part of expiration in the range where the flow is maximal (Fig. 8). This thing is particularly very important during comparative tests of two instruments.

8. CONCLUSIONS

The measuring accuracy of all parameters in forced expiration depends on the method of their definitions: those, calculated at the beginning part of expiration are more accurate. Although volume is the integral of flow it is presented more precisely which is the result of a special form of $V(t)$ function (and $Q(t)$ function). The bigger is the flow and volume the smaller is the measuring error.

The recommendations concerning the technical parameters of the spirometer have been presented in report [1]. Now they should be revised for two causes: the signal's digital conversion can be realized with sufficient and such high accuracy, that the spirometric transducer error's influence becomes more important.

The correction of the air temperature of the surroundings, which is considerably lower than exhaled air, willingly used for the spirometric transducers of the volumetric type cannot be used for the flow transducers. Flowing air is measured very near the mouth (the transducer is placed almost in the mouth) and the changes in its temperature are not considerable. The differences are about (3÷4)°C. It should be recommended to measure the temperature by placing the temperature transducer inside the flow transducer.

Higher flow resistance of the spirometric transducer appears at high flows, which is at the beginning of forced expiration. It can cause difficulties in patient tests at the early stage of pathology in which the respiratory resistance becomes slightly higher.

REFERENCES

[1] R.O. Crapo, "Standardization of spirometry. 1994 update", Am. J. Respir. Crit. Care Med., Vol. 152, pp. 1107–1136, 1995.

[2] M.C. Khoo, "Physiological control systems. Analysis, simulation and estimation", IEEE Press, New York, 2000.

[3] C.A. Volta, Y. Ploysongsang, L. Eltayara, J. Sulc, J. Milic-Emili, "A simple method to monitor performance of forced vital capacity", J. of Appl. Physiol., Vol. 80, No. 2, pp. 693–698, 1996.

[4] I. Madan, P. Bright, M.R. Miller, "Expired air temperature et the mouth during a maximal forced expiratory manoeuvre", Eur. Respir. J., Vol. 6, No. 7, pp. 1556–1562, 1993.

[5] B. Juroszek, "Estimation of measurement accuracy of the mid–expiratory flow parameters MEF", In: Selected papers of the Third National Conference on Biocybernetics and Biomedical Engineering. Pol. Acad. Sc., Vol. 2, pp. 63–74, 1985.

[6] B. Juroszek, "Air features in spirometric transducers", Measurement, Vol. 39, No. 5, pp. 466-476, 2006.

[7] C.H. Buess, U. Boutellier, E.A. Koller, "Pneumotachometers", In: Encyclopedia of medical devices and instrumentation, (J.G. Webster), Vol. 4, Willey New York 1988, pp. 2319–2324.

[8] B. Juroszek, "The error of method in spirometry", Measurement, Vol. 39, No. 5, pp. 458-465, 2006.

[9] B. Juroszek, "Evaluation of the transducer's flow resistance on the spirometric results", Allergy and Asthma Proceedings, 2006 (in press).