Analysis of methods and equipment for inhaled/exhaled airflow rate measurement

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Abstract. The article describes the main methods for inhaled/exhaled airflow rate measurement, which are used in the departments of functional diagnostics. Analysis of the advantages and disadvantages of various measurement methods was performed. Selection of devices and analysis of their technical characteristics were performed according to each method.

1. Introduction
Spirometry is the most effective method of pulmonary function testing. The essence of the method is that a patient undergoes particular breathing tests. Volumetric air flow rate and air volumes are measured at different stages of breathing tests. The analysis of expiratory flow manoeuvre (expiration) provides the most clinically significant data. Currently, up to 50 indicators of pulmonary ventilation function are measured although 10 main indicators are sufficient to establish a diagnosis in most cases.

Technical requirements are specified in the BS EN ISO 23747 and BS EN ISO 26782 standards and Р 50.2.091-2013 ГСИ calibration procedure. Spirometers, spiroscopes and spiroanalyzers. Calibration procedures.

This paper presents methods and equipment for airflow rate measurement.

2. Methods and tools for measuring flow
Currently, there are several techniques used to design sensors for inhaled/exhaled airflow rate measurement. They are divided into the following types: thermal, turbine, hydrodynamic, ultrasound, etc.

Airflow sensors of different types and designs convert different flow characteristics. The measurement method based on the steady-state heat transfer allows obtaining data on the mean mass gas flow rate (kg/sec). The hydrodynamic and mechanical turbine methods provide for measurement of the mean volumetric airflow rate (m3/sec). Electromagnetic and ultrasound sensors are designed for measurement of the mean airflow rate (m/sec). Thermal convection method and hydrodynamic method with the use of the Pitot tube allow for measurement of the local rate of liquid or gas flow.

Main technical parameters of flow sensors:
- Flow measurement range (l/sec): ±14 (inspiration-expiration);
- Flow measurement accuracy: +/-5% or 50 ml/sec;
- Measurement system diameter: 20-80 mm;
- The linearity of characteristic;
- Flow resistance in the PEFM measurement range should not exceed 0.36 kPa/l/sec (0.006 kPa/l/min);
- Sampling frequency: 100-1000 Hz.

2.1. Hydrodynamic flow sensors
Differential pressure sensors (shown in Fig. 1) based on differential manometers are most frequently used in spirometry equipment (both fixed and portable). Fleisch, Pitot, and Lilly tubes fall into this type. Major components of the sensor are a pneumatic resistive element 1 (set of tubes, grid) and differential manometer consisting of two pressure sensors 2 and 4 or one differential pressure sensor. When the airflow passes through the resistive element, a change in pressure takes place and it is recorded by the differential manometer.

![Figure 1. Differential pressure sensor.](image)

A flow rate is a derivative of a function that is the difference in differential pressure and can be deduced from the Bernoulli’s equation:

\[ p = p_t - p_s = \frac{\rho u^2}{2}, \]  

where:
- \( p \) - a difference in pressure (Pa);
- \( p_t \) - total pressure (Pa);
- \( p_s \) - static pressure at the inlet (Pa);
- \( \rho \) - fluid medium density (kg/m³);
- \( u \) - flow rate (m/sec).

Therefore, we use the following equation to calculate the flow rate of an incompressible fluid medium:

\[ u = \sqrt{\frac{2(p_t - p_s)}{p}}. \]  

And we use the following equation to calculate the flow rate of a compressible fluid medium (for example, air):
where: $k = c_p/c_v$ (specific heat ratio).

Disadvantages of the Fleisch tube are flow resistance, low sensitivity at low flow rates and non-linear relationship between the difference in pressure and rate.

Examples of spirometers with sensors based on Fleisch, Pitot, and Lilly tubes.

Spirolan (Lanamedica Ltd., Saint Petersburg) is a computer-based spirometer of pneumotachometric type with an airflow converter based on the Lilly tube and user-friendly interface.

Characteristics:
- Volume: ±12 l;
- Flow measurement range: ±15 l/sec;
- Volume measurement error: less than 3%;
- Flow measurement error: less than 3%;
- Time measurement error: less than 1%;
- Signal bandwidth: 30 Hz.

Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (complies).

Spiro Pro (BTL, Great Britain) is a portable spirometer, which can be connected to the computer, of pneumotachometric type with an airflow converter based on the Lilly tube.

Characteristics:
- Volume: 0.025-8 l;
- Flow measurement range: ±16 l/sec;
- Volume measurement error: less than ±3% or 50 ml/sec;
- Flow measurement error: less than ±5% or 50 ml/sec;
- Flow resistance: <79 Pa/l/sec;
- The effective number of bits of ADC: 15;
- Sampling frequency: 1000 Hz.

Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (not confirmed).

SMP-21/01-“R-D” (RPC Monitor, Ltd., Rostov-on-Don) is a portable spirometer, which can be connected to the computer, of pneumotachometric type with an airflow converter based on the Fleisch tube.

Characteristics:
- Volume: 0.05-10 l;
- Flow measurement range: ±14 l/sec;
- Volume measurement error: less than ±3% or 50 ml/sec;
- Flow measurement error: less than ±5% or 50 ml/sec;
- Flow resistance: ≤150 Pa/l/sec (0-12 l);
- The effective number of bits of ADC: 12;
- Sampling frequency: 1000 Hz.
Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (complies).
Compliance with the requirements of the Р 50.2.091-2013 ГСИ calibration procedure (complies).

2.2. Tachometric flow sensors
Volumetric flow rate sensors of the turbine (tachometric) type, in which airflow turns the turbine, are less frequently used in spirometers. There are optical and inductive turbine sensors.
Fig. 2 shows an optical turbine sensor that consists of the following components:

- Turbine 1 that gives rotatory motion to the airflow;
- Photoradiator 2;
- Impeller breaker 3 and photoreceiver 4.

![Figure 2. Sensor of turbine type.](image)

The airflow is converted into the sequence of electric pulses by way of modulation of electromagnetic radiation using a rotating plate, which is transferred from the photoradiator to the photoreceiver. The inhaled/exhaled airflow acquires an angular rate ($\omega$) proportional to the volumetric flow rate ($Q$) and gives rotatory motion to the turbine.

$$\omega = \frac{Q}{n \frac{d^2}{4} R}$$

(4)

where:
- $d$ - inlet diameter, m;
- $n$ - number of inlets;
- $R$ - radius, on which inlets are located, m.

Disadvantages of turbine sensors are slow response and difficult cleaning since the mechanical effect on the impellers and plate may result in their damage and lead to the loss in sensor reliability. Also, the system response time and the high price of the impeller are among big disadvantages. Advantages of this type of sensors are the transfer linearity, good mass and dimension parameters, good tolerance to interference, and capability to determine the airflow direction. Up-to-date models of industrially manufactured sensors have low pneumatic resistance and sufficiently high sensitivity.

Examples of spirometers with tachometric sensors.
MICRO DL (Micro Medical, Great Britain) is a portable spirometer of tachometric type with an airflow converter based on a turbine.

Characteristics:
- Unidirectional digital turbine sensor;
Resolution: volume - 10 ml, flow - 0.03 l/sec;

Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (complies).

MINISPIR (MIR, Italy) is a portable spirometer of tachometric type with an airflow converter based on a turbine.

Characteristics:

- Flow direction (inspiration/expiration);
- Flow measurement range: ±16 l/sec;
- Volume measurement accuracy: ±3% or 50 ml;
- Flow measurement accuracy: ±5% or 200 ml/sec;
- Dynamic resistance in 0-12 l/sec: <200 Pa/l/sec;
- Temperature sensor (BTPS): (0-45°C) semiconductor.

Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (complies).

2.3. Ultrasonic flow sensors

Ultrasound sensors are less frequently used for the inhaled/exhaled airflow rate measurement. Several of them are widely used, namely:

- Flow rate meters based on the concept that the ultrasound wave propagation speed \( C \) in a moving medium is a vector sum \( C = C_y + V \), where \( C_y \) is a speed of ultrasound waves in the air and \( V \) is an air flow rate.
- Flow rate meters based on the Doppler effect, i.e. ultrasound waves reflect from an object or group of objects moving in the flow.

Piezoelectric transducers (PET) transmit and receive ultrasound vibrations. Piezoelectric transducers are typically produced from lead zirconate titanate (LZT). Advantages of this material are very high electro-acoustic conversion efficiency and high Curie temperature (about 300°C), which reduce the possibility of material depolarization during soldering of transducer outputs. For sensors with small diameter, electro-acoustic transducers are installed in different places. Typically, \( \text{B} \) and \( \Gamma \) versions (Fig. 3) are used.
Figure 3. Ultrasound sensors based on the effect of ultrasound displacement.

The ToF (time of signal flight) value is measured to calculate the flow speed in sensors of B and Г types. T12 - a time of signal propagation, which transits from the first sensor (PET1) to the second sensor (PET2). T21 - a time of signal propagation in the opposite direction.

\[ T_{12} = \frac{L_u - L_d}{C_0} + \frac{L_d}{C_0 - V \cos \alpha}; \]

\[ T_{21} = \frac{L_u - L_d}{C_0} + \frac{L_d}{C_0 + V \cos \alpha}; \]

\[ \Delta t = T_{21} - T_{12}; \]

where:
- Lu - the distance between the membranes of piezoelectric converters, \( \text{mm} \);
- Ld - length of an active part of the acoustic channel, \( \text{mm} \);
- \( C_0 \) - the speed of ultrasound waves in the air, \( \text{m/sec} \);
- \( V \) - flow speed, \( \text{m/sec} \);
- \( \Delta t \) - delta time of ultrasound wave transmission along the flow and against the flow;
- \( \alpha \) - the angle between the sensor axis and PET, degree.

The flow speed (V) shall be calculated after formula (7) as follows:

\[ V = \frac{\Delta t + C_0 \alpha}{2(\Delta t + C_0 \alpha)}; \]

Advantages of the method are excellent accuracy characteristics, the linearity of characteristic, dynamic characteristics, and low flow resistance. Moreover, the sensor of this type can be easily disinfected.

Examples of spirometers with ultrasound sensors.

SpiroScout (GANSHORN, Germany) is a portable spirometer with an airflow converter based on an ultrasound airflow sensor.
- Characteristics:
  - Daily calibration is not required.
  - Flow measurement range: ±18 l/sec;
  - Volume measurement accuracy: ±1% or 50 ml;
  - Flow measurement accuracy: ±2% or 50 ml/sec;
  - No resistance to airflow;
  - Temperature sensor (BTPS): (0-45°C) semiconductor.

Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (not in compliance with the BS EN ISO 26782 standard).

Easy One (NDD, Switzerland) is a portable spirometer with an airflow converter based on an ultrasound airflow sensor.
- Characteristics:
  - Daily calibration is not required.
  - Flow measurement range: ±16 l/sec;
  - Volume measurement accuracy: ±1% or 50 ml;
  - Flow measurement accuracy: ±2% or 50 ml/sec;
  - No resistance to airflow;
  - Temperature sensor (BTPS): (0-60°C) semiconductor.
Compliance with the requirements of the BS EN ISO 23747 and BS EN ISO 26782 standards (not confirmed).
Compliance with the requirements of the Р 50.2.091-2013 ГСИ calibration procedure (complies).

3. Conclusions
It may be concluded from this article that the most relevant sensors for spirometry are ultrasound sensors although they are not in common use. Absence of resistance to airflow, high accuracy, and application of disposable mouthpieces are the advantages that are not available in other methods.

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