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Novel hot-wire based spirometry is highly accurate at low flow rates

Abstract: Spirometry is the most commonly used pulmonary function test. The aim of this comparative study was to evaluate four commercially available spirometers with different measurement principles (turbine-, ultrasound-, differential pressure- and hot-wire anemometer). In particular, the measurement accuracy in breathing manoeuvres with low flow rates was investigated, which is highly relevant for paediatric use. Among the tested devices the hot-wire based spirometer showed the highest measurement accuracy at low flows whilst fully complying with the ATS/ERS standards.

Keywords: spirometry, ATS/ERS Spirometry Standards, pulmonary function testing, respiratory flow rate, turbine anemometer, ultrasound anemometer, differential pressure anemometer, hot-wire anemometer

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1 Introduction

Spirometry measures how an individual inhales or exhales volumes of air as a function of time [1,2]. It is the most widely used non-invasive pulmonary function test for diagnosis of asthma and chronic obstructive pulmonary disease (COPD) [2,3]. Furthermore, it is useful to assess asthma or other causes of airflow obstruction in the evaluation of chronic cough [4].

To date, the use of handheld, flow-sensing spirometers has increased due to several advantages compared to traditional volume-sensing, desktop spirometers e.g. simplicity of use, portability, reduced risk of cross-contamination and lower costs [5]. Furthermore, the importance of spirometry increased among paediatricians since the Federal Joint Committee in Germany updated the disease management program (DMP) for bronchial asthma by including children below the age of five. However, until recently appropriate global lung function reference equations have been lacking, especially for younger children. In an attempt to address these issues, the Global Lung Function Initiative (GLI) recently published the first all-age (3–95 years) reference equations for spirometry [6]. As a consequence, spirometers must be able to deliver reliable and accurate measurements even for small respiratory flow rates as expected in young children or in patients with impaired lung function [6,7].

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2 Methods

In the present study four commercially available spirometers with different measuring principles are tested and compared on the basis of the ATS/ERS standards for spirometry regarding measurement accuracy at low volume rates [7]. In particular, the following devices have been tested:

manufacturer	trade name	measuring principle
CareFusion	MicroLoop	turbine anemometer
Ganshorn	Spiroscout	ultrasound anemometer
Welch-Allyn	SpiroPerfect	differential pressure anemometer
Sendsor	Luftttacho	hot-wire anemometer

Table 1: List of the evaluated commercially available spirometers.

To evaluate the accuracy two different types of respiratory profiles were investigated: (1) Profiles that are modelled after a naturally forced respiratory profile (profile A, EN ISO 23747: 2009) and (2) Artificially defined respiratory profiles with dynamic progression (profile B, EN ISO 23747: 2009).
The selection of these profiles is suitable for simulating flow patterns that occur in the intended patient population.
In the present study a standardized procedure for testing pulmonary function parameters were used. To generate the respiratory profiles, a "Flow / Volume Simulator Series 1120" (Hans Rudolph, Inc.) was used (figure 1). The generator meets the requirements of the standard EN ISO 23747: 2009 for airflow generators to determine the measurement error of spirometers.

Figure 1: Flow / Volume Simulator Series 1120, Hans Rudolph, Inc.).

To carry out the measurements, the tested devices were connected to the airflow generator. All tested devices used the same adapter. The airflow generator was operated by the "Flow Volume Simulator" control program. Five naturally forced respiratory profiles and immediately afterwards five dynamic respiratory profiles with flow values of 10, 30, 50, 100, 200, 300, 400, 600, 800 l/min were measured with each of the devices. Those 720 measurements were repeated on the following day. Before each measurement, additional environmental data, such as atmospheric pressure, room temperature, air temperature and humidity were recorded. The peak expiratory flow readings of the test runs were entered into a spread sheet program (Microsoft Excel). After completion of all test series, the measurement accuracy was assessed with the parameters described in table 2.

Measuring deviation:	To determine the measurement deviation, the maximum difference of 5 measured values of a profile A was calculated and compared with the set value.
Linearity:	To determine the linearity, the difference between the measurement deviations of two consecutive respiratory profiles (profile A) was calculated and compared to the larger average of these respiratory profiles.
Frequency response:	The measurement deviation was calculated from the percentage deviation of the mean values of profile A to the mean values of profile B

Table 2: Criteria for the assessment of measurement accuracy.

3 Results

First, the measurement deviation in naturally forced profiles (profile A) was investigated in the range of 10-800 l/min.
The lowest measurement deviation of about 1% with peak flows ranging from 10 l/min to 300 l/min were achieved with hot-wire anemometry. This range corresponds to male children below 6 years of age. All other tested devices showed a larger measurement error up to 4.5%, which is however medically negligible considering the compliance error (figure 2a).
The assessment of the linearity revealed that the differential pressure based spirometer showed a measurement deviation for a peak flow value of 100 l/min outside the acceptance range which is relevant for male children between 3-6 years of age (figure 2b). In contrast the other spirometers (turbine-, ultrasound- and hot-wire anemometer) fully complied with the ATS/ERS standards regarding accuracy of linearity from 10-600 l/min.

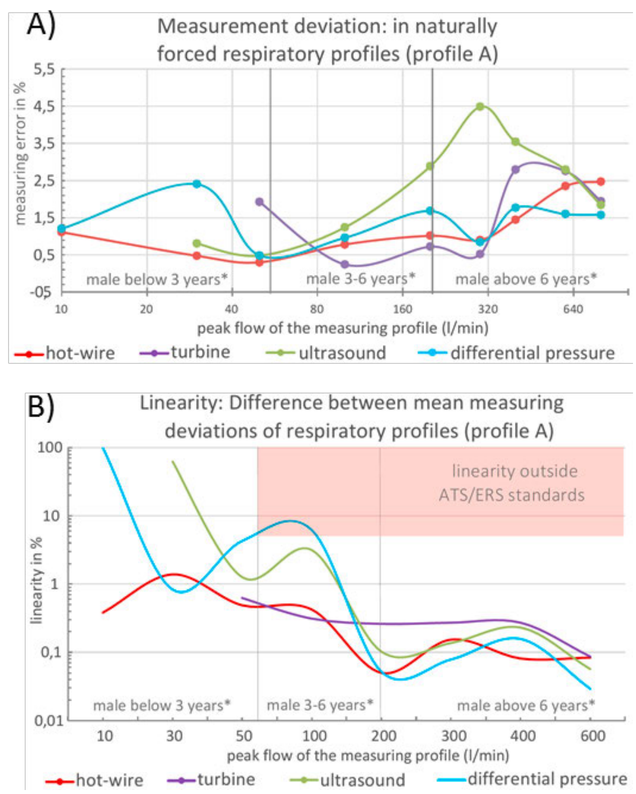

Figure 2: A) The measurement error plotted over the tested profile curves of 10 - 800 l/ min. The vertical lines divide the categories of age-dependent peak flow expectation values. **B)** The linearity plotted over the tested profile curves of 10 - 600 l/min. Linearity that is in the coloured area of the graph is outside the tolerance limits of ATS/ERS standards [7,8,9].

The assessment of the frequency response based on the percentage deviation of the mean values of profile A to the mean values of profile B showed that the differential pressure anemometer is not applicable for children under 6 years because the dynamic measurement error is outside the ATS/ERS standards and thus in a medically unacceptable range (figure 3). The turbine anemometer cannot measure profiles with peak flows below 200 l/min and hence cannot be used for children under the age of 6. Furthermore, the ultrasound anemometer is not suitable for children under 3 years because the dynamic measurement error is in a medically unacceptable range. In addition, this device cannot measure dynamic respiratory profiles with peak flows below 50 l/min. In contrast, the frequency response for the hot-wire anemometer showed acceptable measurement errors below 10% in the studied flow range.

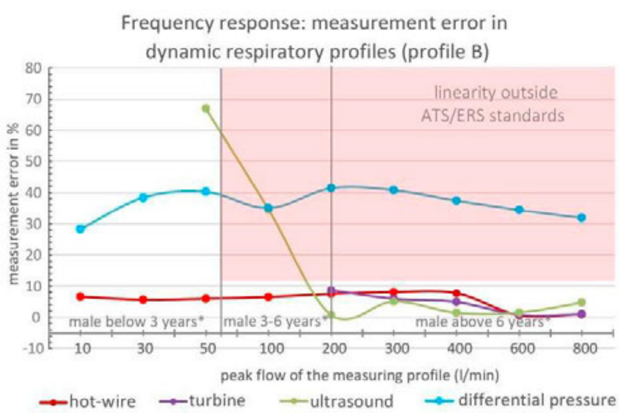

Figure 3. Percentage error measured over the tested profile curves of 10 – 800 l/min. The vertical lines divide the areas of age-dependent peak flow expectation values [7,8,9].

4 Conclusion

Considering the intended patient population of children below 6 years of age, spirometers must be able to measure peak flows in the range from 35 l/min to 622 l/min [8]. The investigated devices with the functional principles ultrasound anemometry and turbine anemometry cannot meet this requirement since they can only be used at a peak flow of 50 l/min or above 200 l/min, respectively. The hot wire anemometer shows the highest measuring accuracy of all tested spirometers over the measured peak flow range, both in naturally forced respiratory profiles and in respiratory profiles, which are characterized by a short rise and dwell time resulting in a very dynamic course. In a direct comparison of hot-wire anemometer with the differential pressure method, hot-wire anemometer shows a higher accuracy for the application. Especially at dynamic respiratory profiles, the differential pressure anemometry measurement error of over 30% is unacceptable. The hot-wire anemometer is the only spirometer among the tested devices that fully complies with the accuracy requirements according to ATS/ERS standards and can be applied for children below 5 years. In conclusion, the high measuring accuracy in the lower flow range makes spirometry based on hot-wire anemometry best tailored for use in paediatric spirometry.

Author Statement

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