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Spirometers

Educational aims

- To outline the characteristics of currently available types of spirometer.
- To explain the requirements a spirometer should fulfil.

Summary

There are many spirometers on the market. They can be divided roughly into a group that primarily measures volume and a group that primarily measures flow. Quality control and calibration should be performed on a regular basis to ensure that a device (still) functions appropriately. The types have different characteristics and are optimal for different circumstances (from a simple peak-flow meter to monitor asthma at home to an ultrasonic device to measure a patient in a pulmonary function lab). In this article, the characteristics of the currently available spirometers are discussed, as well as the requirements they should fulfil.

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From cheap and easy devices usually seen in primary care settings, to the sophisticated and expensive devices used in pulmonary function labs, the range of spirometers on the market is huge. Simple versions are capable of measuring basic values such as vital capacity (VC), forced expiratory volume in one second (FEV_1) and peak expiratory flow (PEF), while others are capable of displaying almost any lung function parameter imaginable. There are many different ways to measure the flows and/or volumes generated by the respiratory system. An anatomical cast of a lung shows the complexity of the system that we want to quantify in a few parameters which are of maximal clinical relevance (figure 1). Since the values of these parameters often change slowly with age, the measurement system (*i.e.* the spirometers) needs to measure as accurately and reproducibly as possible.

Spirometers can be divided into two basic groups.

- Volume-measurement devices (*e.g.* wet and dry spirometers).
- Flow-measurement devices (*e.g.* pneumotachographsystems, mass flow meters).

In the first case, the flow is calculated by the time derivative of the volume signal. In the second case, volume is calculated by integration over time of the flow signal.

An American Thoracic Society (ATS)/European Respiratory Society task force on the standardisation of lung function testing has written articles containing a great deal of detailed information about spirometry. The tables and some of the information in the present article are taken from the second paper in the series [1]. In brief, the requirements of an acceptable spirometer are:

- Spirometers must be able to accumulate volume for ≥15 s.
- The measuring volume should be ≥8 L (body temperature and pressure, saturated).
- The accuracy of reading should be at least ±3% (or ±0.05 L) with flows from 0–14 L per s.

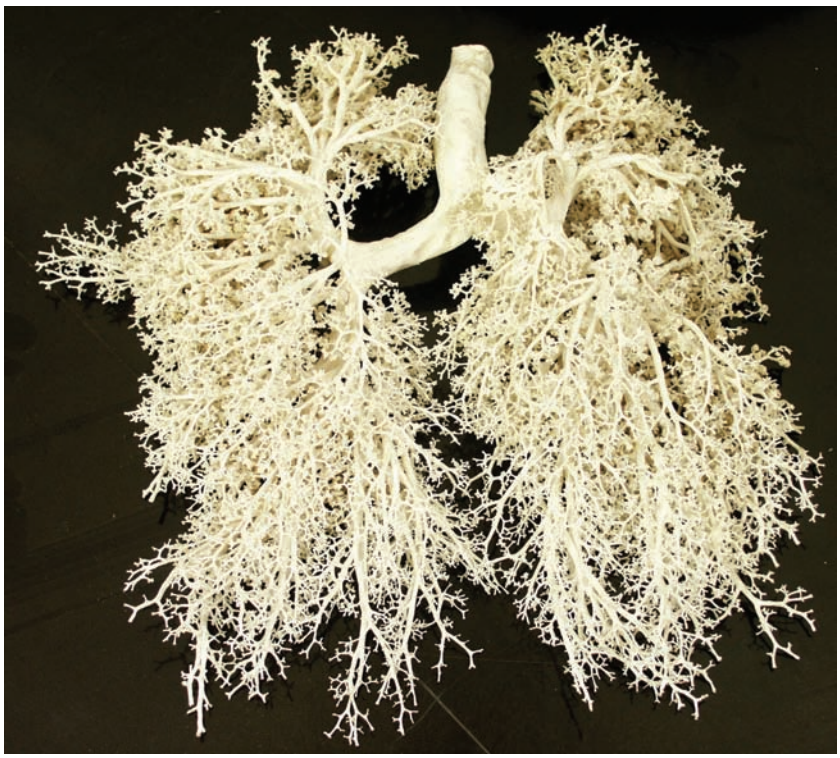

Figure 1
A cast of a pair of human lungs.
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- The total resistance to airflow at 14 L per s should be <1.5 cmH_2O per L per s (<0.15 kPa per L per s).

These requirements are laid out in more detail in table 1. They should be met with all filters and tubing, *etc.*, in place. The device should be capable of performing up to eight forced VC (FVC) measurements in 10 min (the criteria above should be met each time). Note that the qualities of filters may change in resistance due to moisture.

Graphical display requirements are summarised in table 2.

Calibration and linearisation of spirometers varies between devices. Simple spirometers are often factory-calibrated and cannot be calibrated by the user (this is true of many disposable flow sensors). Others allow a zero-flow calibration or a known volume (from a calibration syringe) may be used as calibration signal. In the three-flow protocol, a known volume is given at three different flow rates. A more sophisticated method is to test a spirometer using a device that is able to generate the 24 ATS standard volume–time waveforms [2]. Last but not least, a biological control may be used. Often this is a respiratory technician working in the lab (therefore it is often a young, healthy person), but preferably people of different sizes and ages should be used.

Table 3 outlines a suggested maintenance and quality-control schedule.

Types of spirometer

Volume-measurement spirometers

Wet spirometers measure volume directly and are therefore accurate for important parameters such

Table 1 Range and accuracy recommendations specified for forced expiratory manoeuvres

Test	Range/accuracy (BTPS)	Flow range L per s	Time s	Resistance and back pressure	Test signal
VC	0.5–8 L, ±3% of reading or ±0.050 L, whichever is greater	0–14	30		3-L calibration syringe
FVC	0.5–8 L, ±3% of reading or ±0.050 L, whichever is greater	0–14	15	<1.5 cmH_2O per L per s (0.15 kPa per L per s)	24 ATS waveforms, 3-L calibration syringe
FEV_1	0.5–8 L, ±3% of reading or ±0.050 L, whichever is greater	0–14	1	<1.5 cmH_2O per L per s (0.15 kPa per L per s)	24 ATS waveforms
Time zero	The time point from which all FEV_t measurements are taken			Back extrapolation	
PEF	Accuracy: ±10% of reading or ±0.30 L per s (20 L per min), whichever is greater; repeatability: ±5% of reading or ±0.15 L per s (10 L per min), whichever is greater	0–14		Mean resistance at 200, 400, 600 L per min (3.3, 6.7, 10 L per s) must be <2.5 cmH20 per L per s (0.25 kPa per L per s)	26 ATS flow waveforms
Instantaneous flows (not PEF)	Accuracy: ±5% of reading or ±0.200 L per s, whichever is greater	0–14		<1.5 cmH20 per L per s (0.15 kPa per L per s)	Data from manufacturers
$FEF_{25–75\%}$	7.0 L per s, ±5% of reading or ±0.200 L per s, whichever is greater	±14	15	Same as FEV1	24 ATS waveforms
MVV	250 L per min at V_T of 2 L within ±10% of reading or ±15 L per min, whichever is greater	±14 (±3%)	12–15	<1.5 cmH20 per L per s (0.15 kPa per L per s)	Sine wave pump

BTPS: body temperature and ambient pressure saturated with water vapour; FVC: forced vital capacity; FEV_t: forced expiratory volume in t seconds; $FEF_{25–75\%}$: mean forced expiratory flow between 25% and 75% of FVC; MVV: maximum voluntary ventilation; V_T: tidal volume. Reproduced from [1].

Table 2 Recommended minimum scale factors for time, volume and flow on graphical output

Parameter	Instrument display		Hardcopy graphical output	
	Resolution required	Scale factor	Resolution requred	Scale factor
Volume#	0.050 L	5 mm per L	0.025 L	10 mm per L
Flow#	0.200 L per s	2.5 mm per L per s	0.100 L per s	5 mm per L per s
Time	0.2 s	10 mm per s	0.2 s	20 mm per s

#: the correct aspect ratio for a flow versus volume display is two units of flow per one unit of volume

Table 3 Summary of equipment quality control

Test	Minimum interval	Action
Volume	Daily	Calibration check with a 3-L syringe
Leak	Daily	3 cmH_2O (0.3 kPa) constant pressure for 1 min
Volume linearily	Quarterly	1-L increments with a calibrating syringe measured over entire volume range
Flow linearily	Weekly	Test at least three different flow ranges
Time	Quarterly	Mechanical recorder check with stopwatch
Software	New versions	Log installation date and perform test using "known" subject

as FEV_1 and the VC. They are simple, understandable (good for teaching), no electronics are needed and there is a direct overview of the values measured. On the other hand, these devices are no longer produced, have a limited range of parameters (*e.g.* maximum expiratory flow at 25% of VC is very difficult to obtain) and may have problems caused by the inertia of the moving drum, which may lead to an overshoot of the volumes measured.

Dry spirometers (*e.g.* dry rolling seal or bellows) generally have better frequency characteristics and are more easy to automate, but they too are almost unobtainable.

Flow-measurement spirometers

The most widely used system in pulmonary function labs is the pneumotachograph spirometer. Early systems had a Fleisch or Lilly pneumotachograph, while nowadays the pressure drop over a resistance (a heated fine mesh) is measured. The pressure drop divided by the resistance of the pneumotachograph yields the flow, which can be transformed into a volume by time integration.

These devices have no moving parts, have good frequency characteristics and are simple to automate, but since the volume is calculated by time integration, calibration is difficult (the calibration signal is normally a syringe, which generates a fixed volume rather than a known flow). Also, linearity may be a problem if the flow is not laminar, and the devices can become contaminated by sputum or moisture, which condenses on the mesh. To (partially) avoid this problem, the mesh is often heated and a filter can be used.

Spirometers based on the principle of a rotating vane do not need to be heated, which should ensure that better linear and high ranges of flows are possible. Such devices are often used for office spirometry and also during maximal ergometry. A disadvantage is that they have moving parts (the rotating vane), which are fragile and easily broken. Their low-flow characteristics are dubious (it takes a certain flow-rate before the vane begins to rotate) and at high flows the vane may continue rotating due to inertia after the flow has stopped.

Mass flow sensors (anemometers) are based on heated wires that are cooled by the flow of air generated by the patient. They have no moving parts, are independent of air temperature, moisture or viscosity, have good frequency characteristics and are simple to automate. However they are non-linear (requiring a difficult software correction) and often unstable. The sensor-resistance is connected in series with cables and connectors, and changes in those components are also measured as if they were air-flows. These devices can be used in humid, pressurised environments (for instance, for ventilated patients), whereas other spirometers have difficulties under these conditions.

The most modern spirometers often contain an ultrasonic flow-head. They have no moving parts, have no resistance (nothing is blocking the flow) and have good frequency characteristics. The signal depends in general on the air-mixture,

temperature, moisture and pressure. This is both a difficulty and an advantage, since a lot of other measurements may be performed with the same sensor (especially when using gases with a different molecular weight like SF_6). However, by clever choices the flow can be calculated independently of gas composition, temperature, humidity and pressure. A drawback is that these sensors are often more expensive.

Accuracy

Peak-flow meters should ideally have a flat frequency response (±5%) up to 15 Hz. Their accuracy should be at least ±10% or ±0.3 L per s (20 L per min) whichever is greatest. Mean resistance should be <2.5 cmH_2O per L per s (0.25 kPa per L per s).

Maximal voluntary ventilation (MVV) should be tested under ambient conditions with a 2-L syringe with sinusoidal flow patterns (ATS flow-time waveforms 1, 4, 8 and 25 [2]). The accuracy should be at least ±10.5% or ±20 L per min, whatever is greatest. The pressure at the mouthpiece should not exceed ±10 cmH_2O (1 kPa) during the entire test. Body temperature and pressure, saturated (BTPS) testing is not required.

Calibration

Most spirometers need an ambient temperature and pressure (ATP)-BTPS correction. Inhaled air (at 37°C) fully saturated has a water vapour pressure of 47 mmHg, so the partial pressure in the lung is 760 - 47 = 713 mmHg

Using the ideal gas law (pressure × volume = n × ideal gas constant × temperature in Kelvin), the change in the volume of air between the lungs and ambient conditions can be calculated. The correction factor is often ~7–8%.

Filters

A common question is whether spirometers should be used in combination with filters. When a patient inhales from a device, everything should be cleaned (flush a closed system with at least five times the maximal volume of that system). The tubing, mouthpiece and resistive device should be replaced. The alternative is to use a low-resistance one-way valve, or to use disposable filters and/or disposable (flow) sensors or inserts. Manufacturers have a responsibility to make devices that are easy to dismantle and to clean. The purchaser should always ask the manufacturer how a device can be cleaned.

Conclusion

There are many devices on the market that can measure flow and/or volume. They range from simple devices like peak-flow meters to advanced ultrasonic flow-heads. Depending on the goal, the appropriate device should be chosen. Measuring the flows of a ventilated patient may require a different spirometer than that used for a healthy athlete during maximal effort. In this article, requirements are given for accuracy and quality control of spirometers. Although the majority of spirometers will fulfil most of the requirements, one should always test the devices with known volumes/flows or biological controls to check a device is working properly. Besides that, it is critical that a device is operated by a professional, since for instance an unnoticed suboptimal effort of a healthy adult on a perfect device may lead to a reduced FEV_1, while that same suboptimal effort from a severe COPD patient may result in an increased FEV_1. In both cases, this may result in incorrect clinical conclusions.

References

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