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SERIES "ATS/ERS TASK FORCE: STANDARDISATION OF LUNG FUNCTION TESTING"
Edited by V. Brusasco, R. Crapo and G. Viegi
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General considerations for lung function testing

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BACKGROUND

In preparing the joint statements on lung function testing for the American Thoracic Society (ATS) and the European Respiratory Society (ERS), it was agreed by the working party that the format of the statements should be modified so that they were easier to use by both technical and clinical staff. This statement contains details about procedures that are common for many methods of lung function testing and, hence, are presented on their own. A list of abbreviations used in all the documents is also included as part of this statement.

DEFINITIONS

All terms and abbreviations used here are based on a report of the American College of Chest Physicians/ATS Joint Committee on Pulmonary Nomenclature [1]. The metrology definitions agreed by the International Standards Organization (ISO) are recommended [2] and some important terms are defined as follows.

Accuracy is the closeness of agreement between the result of a measurement and the conventional true value.

Repeatability is the closeness of agreement between the results of successive measurements of the same item carried out, subject to all of the following conditions: same method, same observer, same instrument, same location, same condition of use, and repeated over a short space of time. In previous documents, the term reproducibility was used in this context, and this represents a change towards bringing this document in line with the ISO.

Reproducibility is the closeness of agreement of the results of successive measurements of the same item where the individual measurements are carried out with changed conditions, such as: method of measurement, observer, instrument, location, conditions of use, and time. Thus, if a technician tests a subject several times, this is looking at the repeatability of the test. If the subject is then given a bronchodilator drug and tested again after 30 min, one needs to know the reproducibility of the test in order to make a decision on this comparison.

The measurement range for a recording device is the range over which the manufacturer indicates the device complies with the recommendations below.

Equipment resolution is the smallest detectable change in measurement.

PATIENT CONSIDERATIONS

Contraindications

Performing lung function tests can be physically demanding for a minority of patients. It is recommended that patients should not be tested within 1 month of a myocardial infarction. Patients with any of the conditions listed in table 1 are unlikely to achieve optimal or repeatable results.

TABLE 1 Conditions where suboptimal lung function results are likely

Chest or abdominal pain of any cause
Oral or facial pain exacerbated by a mouthpiece
Stress incontinence
Dementia or confusional state

Position

Testing may be performed either in the sitting or standing position, and the position should be recorded on the report [3, 4]. Sitting is preferable for safety reasons in order to avoid falling due to syncope. The chair should have arms and be without wheels. If a wheelchair is used, the wheels should be locked. If the standing position is used, a chair can be placed behind the patient/subject, so that they can be quickly and easily moved into a sitting position if they become lightheaded during the manoeuvre. Obese subjects, or those with excessive weight at the mid-section, will frequently obtain a deeper inspiration when tested in the standing position. Consequently, forced expiratory volumes and flows may improve with the standing position in these individuals. Normal-weight subjects typically have equivalent values when tested sitting or standing, but, for longitudinal studies, the same test position should be used each time.

PATIENT DETAILS

Age, height and weight

The patient's age, height and weight (wearing indoor clothes without shoes) are recorded for use in the calculation of reference values. The age should be expressed in years. Height and weight should be expressed with the units in use in the country, corresponding to the ones of the selected reference equation. Body mass index should be calculated as $kg \cdot m^{-2}$. The height should be measured without shoes, with the feet together, standing as tall as possible with the eyes level and looking straight ahead, and using an accurate measuring device. For patients with a deformity of the thoracic cage, such as kyphoscoliosis, the arm span from fingertip to fingertip can be used as an estimate of height. Arm span should be measured with the subject standing against a wall with the arms stretched to attain the maximal distance between the tips of the middle fingers. A regression equation using arm span, race, sex and age has been found to account for 87% of the variance in standing height [5], with the standard error of the estimate for height ranging from 3.0 to 3.7 cm. Using fixed arm-span ratios (*e.g.* height=arm span/1.06) estimated the standing height reasonably well, except at the extremes, but was always inferior to the regression equation. Estimating height in this way introduces a further level of uncertainty with regard to the predicted value of the lung function index, and the use of fixed ratios has been shown to lead to misclassification of disease [6]. The use of knee height to predict height can also be used for handicapped people where arm span may be difficult to measure [7, 8].

Therapy

The operator should record the type and dosage of any (inhaled or oral) medication that may alter lung function and when the drugs were last administered.

Subject preparation

Subjects should avoid the activities listed in table 2, and these requirements should be given to the patient at the time of making the appointment. On arrival, all of these points should be checked, and any deviations from them recorded.

TABLE 2 Activities that should preferably be avoided prior to lung function testing

Smoking within at least 1 h of testing
Consuming alcohol within 4 h of testing
Performing vigorous exercise within 30 min of testing
Wearing clothing that substantially restricts full chest and abdominal expansion
Eating a large meal within 2 h of testing

Subjects should be as relaxed as possible before and during the tests. The decision to avoid long- and short-acting bronchodilators is a clinical one, dependent on the question being asked. If the study is performed to diagnose an underlying lung condition, then avoiding bronchodilators is useful. If the study is carried out to determine a response to an existing therapeutic regimen, then one may choose not to withhold bronchodilator medications.

Patients should be asked to loosen tight-fitting clothing. Dentures should normally be left in place; if they are loose, they may interfere with performance and are, therefore, best removed.

LABORATORY DETAILS

Ambient temperature, barometric pressure and time of day must be recorded. Temperature is an important variable in most pulmonary function tests and is often measured directly by the instrument. The way in which it is measured and used may vary from instrument to instrument. For example, it may be measured with a simple thermometer or an internal thermistor. Regardless of the method used, it is the responsibility of the laboratory to confirm the accuracy of temperature measurements, and it is the responsibility of the manufacturer to describe or provide a clear mechanism for checking the accuracy of instrument temperature measurements. They should also provide instructions on how to respond when acceptable temperature performance cannot be confirmed.

Ideally, when patients return for repeat testing (*e.g.* at a clinic), the equipment and the operator should be the same, and the time of day should be within 2 h of previous test times.

The order for performing lung function tests should take into account the optimum work flow in the laboratory, potential influences of one test on another and the ability of the subject to undertake the test. One possible order is shown in table 3.

There should be appropriate delays between tests, as indicated in the subsequent sections of this series of documents. Other orders of testing are acceptable (*e.g.* static lung volumes, diffusing capacity, dynamic studies, inhalation of bronchodilator agent and then repeat dynamic studies, as taken from table 3), but the order should be kept constant to avoid introducing unanticipated variability to test results. The choice of order of testing should consider the potential effect of one test on the subsequent test. For example, the measurement of carbon monoxide diffusing capacity of the lung ($D_{L,CO}$) immediately after a nitrogen washout measurement of the total lung capacity (TLC) will be affected by the increased oxygen content in the lungs, unless enough time has passed to allow the oxygen concentration to return to normal. Also, tidal breathing manoeuvres may be disturbed by a recently performed maximal forced expiratory manoeuvre. Bronchodilator administration may affect static lung volumes, reducing hyperinflation by up to 0.5 L [9]. While bronchodilators do not seem to affect diffusing capacity when measured by the Jones–Meade method, they may allow ~10% of patients to obtain a measurement of diffusing capacity that was not possible pre-bronchodilator [10].

TABLE 3 Possible order for undertaking lung function tests in a laboratory

Dynamic studies: spirometry, flow–volume loops, PEF
Static lung volumes
Inhalation of bronchodilator agent (if used)
Diffusing capacity
Repeat dynamic studies (if a bronchodilator was given)

PEF: peak expiratory flow.

HYGIENE AND INFECTION CONTROL

The goal of infection control is to prevent the transmission of infection to patients/subjects and staff during pulmonary function testing. The number of documented cases of infection transmission is very small, but the potential is real (see *Level of infection risk* section). This set of recommendations focuses on equipment used to measure spirometry, diffusing capacity and lung volumes. Organisms may also be transmitted *via* pulse oximeter probes and nebulisers used to administer bronchodilators [11, 12]. Although infection risks increase with exposure to blood, this document does not deal with the risks of arterial blood gases. Pulmonary laboratories performing blood gas analysis should follow the same infection-control procedures used by their clinical laboratory.

Infection can be transmitted by direct contact or by indirect means, which is discussed as follows.

Transmission by direct contact

There is potential for transmission of upper respiratory diseases, enteric infections and blood-borne infections through direct contact. Although hepatitis and HIV contagion are unlikely *via* saliva, transmission becomes a possibility with open sores on the oral mucosa or bleeding gums. The most likely surfaces for contact are mouthpieces and the immediate proximal surfaces of valves or tubing.

Transmission by indirect contact

There is potential for transmission of tuberculosis (TB), various viral infections, opportunistic infections and nosocomial pneumonia through aerosol droplets. The most likely surfaces for possible contamination by this route are mouthpieces, proximal valves and tubing.

Prevention

Transmission to technicians

Prevention of infection transmission to technicians exposed to contaminated spirometer surfaces can be accomplished through proper hand washing and use of barrier devices, such as suitable gloves. To avoid technician exposure and cross-contamination, hands should be washed immediately

after direct handling of mouthpieces, tubing, breathing valves or interior spirometer surfaces. Gloves should be worn when handling potentially contaminated equipment if the technician has any open cuts or sores on his/her hands. Hands should always be washed between patients. Indications and techniques for hand washing during pulmonary function testing have previously been reviewed [13].

Cross-contamination

To avoid cross-contamination, reusable mouthpieces, breathing tubes, valves and manifolds should be disinfected or sterilised regularly. Mouthpieces, nose clips and any other equipment that comes into direct contact with mucosal surfaces should be disinfected, sterilised or, if disposable, discarded after each use. The optimal frequency for disinfection or sterilisation of tubing, valves or manifolds has not been established. However, any equipment surface showing visible condensation from expired air should be disinfected or sterilised before reuse.

Since the use of cold sterilising agents is not without risk, laboratory staff should take care to follow the manufacturer's recommendations concerning proper handling of these products. Some respiratory equipment may be damaged by some methods of sterilisation. For example, heat sterilisation or cold sterilisation chemicals could damage some flow sensors, tubing or seals. Manufacturers should explicitly describe acceptable methods of cleaning and disinfecting their equipment, including recommended chemicals and concentrations, as well as safety precautions for the technicians. Manufacturers' recommendations should be followed; however, a hospital infection-control department's requirements will probably supersede both manufacturers' recommendations and those in this document. If hospital infection-control recommendations have the potential to harm instruments, compromises may have to be negotiated.

Volume-based spirometers

Volume-based spirometers used with a closed-circuit technique should be flushed between subjects with room air at least five times over the entire volume range of the spirometer to enhance clearance of droplet nuclei. The breathing tube and mouthpiece should be decontaminated or changed between patients.

When the open-circuit technique is used and the patient/subject only exhales into the spirometer, only the portion of the circuit through which rebreathing occurs must be decontaminated between patients. For example, when a pneumotachometer system is used, either avoid having the patient inspire through the device, or decontaminate or replace the resistive element and tubing between subjects. Alternatively, a disposable sensor may be used. Disposable sensors, when appropriately used, avoid the need for decontamination of sensors and mouthpieces (see *Disposable in-line filters* section).

When an open-circuit technique (either volume or flow spirometers) is used without inspiration from the measuring system, only the mouthpiece would need to be changed or decontaminated between subjects. However, it is difficult, if not impossible, to assure that patients do not inhale through the device. A low-resistance one-way valve may be used to prevent inhalation, and, if used, must be demonstrated not to alter the spirometric measurements. Not having patients inspire through the device may make it difficult to assess test quality because of the absence of an inspiratory tracing. Hence, this technique should be used with caution. Disassembling, cleaning and/or sensor replacement will usually require recalibration of the spirometer.

Tuberculosis

In settings where TB or other diseases that are spread by droplet nuclei are likely to be encountered, proper attention to environmental engineering controls, such as ventilation, air filtration or ultraviolet decontamination of air, should be used to prevent disease transmission.

Haemoptysis and oral lesions

Special precautions should be taken when testing patients with haemoptysis, open sores on the oral mucosa or bleeding gums. Tubing and breathing valves should be decontaminated before reuse, and internal spirometer surfaces should be decontaminated with accepted disinfectants for blood-transmissible agents.

Other known transmissible infectious diseases

Extra precautions should be taken for patients with known transmissible infectious diseases. Possible precautions include the following: 1) reserving equipment for the sole purpose of testing infected patients; 2) testing such patients at the end of the day to allow time for spirometer disassembly and disinfection; and 3) testing patients in their own rooms with adequate ventilation and appropriate protection for the technician.

Disposable in-line filters

These may be an effective and less expensive method of preventing equipment contamination. The influence of commercially available in-line filters on forced expiratory measures, such as forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) has not been well characterised. A low-impedance barrier device was found not to have a significant effect on FVC and FEV_1 [14], whereas a barrier filter has been shown to cause small but significant reductions in FEV_1 (-44 mL) and peak expiratory flow (PEF; -0.47 $L \cdot s^{-1}$), but did not appear to affect $D_{L,CO}$, alveolar volume or TLC [15]. Although significant differences between measurements with and without filters have been demonstrated for FVC, FEV_1, airway resistance and specific airway conductance (sG_{aw}) [16], these differences were unrelated to the average values of the measurements (except for sG_{aw}), and the limits of agreement were within the range of intra-individual short-term repeatability for almost all of the function indices. Thus, the effect of a filter with optimal characteristics is not considered to be clinically significant, and no appreciable classification error was found in diagnostic tests.

If in-line filters are used, the measuring system should meet the minimum recommendations for accuracy, precision (reproducibility), flow resistance and back pressure with the filter installed. Airflow resistance must be measured with in-line filters in place if that is how patients are tested. Manufacturers of in-line filters should provide evidence that

their filter does not alter standard lung function measurements (vital capacity, FVC, FEV_1, PEF, mean forced expiratory flow between 25% and 75% of FVC, TLC and $D_{L,CO}$).

In the absence of evidence for infection transmission during pulmonary function testing, and the absence of a clear-cut benefit, the regular use of in-line filters is not mandated when the precautions described in the previous *Prevention* sections are followed.

Use of such filters is an area of controversy. On the one hand, some spirometric equipment, particularly those incorporated in multipurpose testing systems, employ valve manifolds, which are situated proximal to breathing tubes. These valve arrangements provide internal surfaces on which the deposition of expired aerosol nuclei is likely. Given their complexity, they may be difficult to disassemble and disinfect between subjects. To the extent that in-line filters have been shown to remove microorganisms from the expiratory air stream and, thus, prevent their deposition as aerosol nuclei on spirometer surfaces, their use may be indicated. On the other hand, in-line filters have been relatively inefficient in excluding microorganisms at the high flows often seen in pulmonary testing, and instrument contamination has been observed when filters have been used [17–20]. However, barrier filters with a high efficiency (>99%) for excluding bacteria have been reported [21, 22], but their performance in excluding smaller microorganisms such as viruses is unknown. A reduction in overall costs with in-line filters, as compared with a disinfection approach to hygiene, in a pulmonary laboratory has been reported [17].

The use of in-line filters does not eliminate the need for regular cleaning and decontamination of lung function equipment.

Equipment design

Manufacturers of lung function equipment are encouraged to focus on designs that can be easily disassembled for cleaning and disinfection. Purchasers of pulmonary function equipment are encouraged to inquire about cleaning and disinfection issues prior to purchase of an instrument, which should involve an evaluation of the ease of cleaning and the clarity of written instructions, and an understanding of what equipment and chemicals will be required.

Level of infection risk

Lung function equipment has not been directly implicated in the transmission of infections, although there is indirect evidence of infection transmission during pulmonary function testing. Organisms from the respiratory tract of test subjects have been recovered from mouthpieces and the proximal surfaces of tubing through which subjects breathe [19, 23]. The flows generated during spirometric manoeuvres may be high enough to aerosolise contaminant organisms, although such aerosolisation has not been demonstrated. There is one case report of a TB skin-test conversion following exposure to a spirometer previously used to test a patient with documented TB [24]. Likewise, there is circumstantial evidence that contaminated lung function equipment may be implicated in increasing the prevalence of *Burkholderia cepacia* infections among cystic fibrosis patients at one centre [25]. There is evidence that pneumotachometer-based systems are less susceptible to bacterial contamination than water-sealed spirometers [26]. In addition, it is well documented that community water supplies can be contaminated with *Mycobacteria* spp. and *Pseudomonas aeruginosa* organisms [27–29]. Thus, there is a potential for both patients/subjects and healthcare workers to deposit microorganisms onto spirometer surfaces (including mouthpieces, nose clips, tubing and any internal or external machine surface), which could subsequently come into direct or indirect contact with other patients or healthcare workers.

This does not pose an appreciable threat to patients/subjects/workers with competent immune systems. It has been argued that immunocompromised patients may require only a relatively small infective dose of either opportunistic organisms or common pathogens for infection to occur. However, there is no direct evidence that routine pulmonary function testing poses an increased risk of infection to immunocompromised patients.

Concerns for the protection of immunocompromised patients, along with increased public and provider awareness of hospital infection-control issues since the 1990s, has led many laboratory directors to routinely use in-line filters to reassure patients and laboratory personnel that their protection has been considered.

PERSONNEL QUALIFICATIONS AND TECHNICIAN'S ROLE IN QUALITY CONTROL

Personnel qualifications

Previously, the ATS has published recommendations for laboratory personnel conducting pulmonary function tests [30]. Minimum requirements include sufficient education and training to assure that the technician understands the fundamentals of the tests, the common signs of pulmonary diseases and the management of the acquired pulmonary function data. The ATS also recommended that medical directors should have appropriate training and be responsible for all pulmonary function testing [31]. Since these initial recommendations, pulmonary function testing equipment and procedures have become considerably more complex. The use of computers has reduced the need for routine manual measurement; however, new and more complex training issues have evolved. Many providers of pulmonary function training programmes have expanded the scope and length of training to accommodate these new needs.

The current guidelines suggest that completion of secondary education and at least 2 yrs of college education would be required to understand and fulfil the complete range of tasks undertaken by a pulmonary function technician.

For pulmonary function testing, an emphasis on health-related sciences (nursing, medical assistant, respiratory therapy, *etc*.) is desirable. Formal classroom-style training alone does not, however, establish competency in pulmonary function testing. Technicians who conduct pulmonary function testing need to be familiar with the theory and practical aspects of all commonly applied techniques, measurements, calibrations, hygiene, quality control and other aspects of testing, as well as having a basic background knowledge in lung physiology and pathology. In the USA, the National Institute for Occupational

Safety and Health (NIOSH) has developed a model programme, and reviews and approves spirometry training courses. These 2- and 3-day courses include the fundamentals of spirometry standards and hands-on training. The workshop experience provides hands-on instruction in a small group setting with an experienced instructor. Students are expected to demonstrate their ability to properly prepare and administer a spirometric test, and demonstrate competency in other areas, such as calibration, recognition of unacceptable manoeuvres, *etc*.

This standard recommends training similar to the NIOSH-approved spirometry programme. Competency is demonstrated by passing a written and practical examination in the presence of an experienced instructor (*i.e.* hands-on testing and calibration). In Europe, training is being carried out differently in various countries. The ERS, through a specific Assembly (Assembly 9 for Allied Respiratory Professionals), regularly delivers relevant postgraduate course training at their annual Congress.

Spirometry refresher training is also recommended. Refresher training helps to ensure that testing technicians are informed of changes in spirometry standards and learn new skills. It also provides a mechanism for technicians to obtain answers to questions not foreseen during initial training. The need for refresher training has been recognised by several organisations, including the Lung Health Study [32], the National Health and Nutrition Examination Survey [33, 34] and the American College of Occupational and Environmental Medicine [35]. The frequency of refresher training is dependent on many factors that differ among individuals. A recommended frequency of every 3–5 yrs is recommended, or shortly after changes to lung function standards are published. While in-house training may achieve the desired goals, laboratory directors should strongly consider the benefits of formal training programmes from outside providers.

Technician's role in quality control

Quality control is important to ensure that the laboratory is consistently meeting appropriate standards. In any quality-control programme, an important element is a manual of procedures that contains the following: calibration procedures, test-performance procedures, calculations, criteria, reference values source, and action to be taken when ''panic'' values are observed. A notebook or an equivalent method of recording and later producing these results should be maintained, which documents the daily instrument calibration, as well as any problems encountered with the system, corrective action required, and system hardware and software upgrades. Records of anomalous events involving either patients/subjects or the technician should be documented with the results of subsequent evaluation and responses to the event. The technician should also maintain records of continuing education and the results of evaluation and feedback provided by the medical director. The ATS has produced a complete procedure manual (Pulmonary Function Laboratory Management and Procedure Manual), which is available in paper and electronic format (www.thoracic.org/education/labmanual.asp), so as to be modifiable by laboratories to meet their individual needs.

In Europe, technical information on lung function tests is contained in a series of publications in the *European Respiratory Journal* [36–42].

Perhaps the most important component in successful pulmonary function testing is a well-motivated, enthusiastic technician. The importance of a quality-control programme with feedback to technicians in obtaining adequate spirometry results has been documented [32]. A quality-control programme that continuously monitors technician performance is critical to the collection of high-quality data. Feedback to the technicians concerning their performance should be provided on a routine basis, which should include, at a minimum: 1) information concerning the nature and extent of unacceptable manoeuvres and nonreproducible tests; 2) corrective action that the technician can take to improve the quality and number of acceptable manoeuvres; 3) positive feedback to technicians for good performance; and 4) comments regarding system set-up and reporting results.

Manufacturers are encouraged to include quality-control aids in their software packages. However, technicians should be trained not to rely exclusively on these quality-control prompts, since technical errors may occur that are not among those recognised by the software. An example of a quality-control aid is a calibration-logging program, which stores the date, time, technician name and the results of routine daily calibration checks. Additionally, the program could issue a warning if an acceptable daily calibration check has not been performed.

REFERENCE VALUES

Detailed statements on the selection of reference values and interpretation of lung function tests have been published [39, 41–43] and new recommendations have just been created [44]. In selecting appropriate reference values, it is important to choose a source that used similar equipment and had a test population that included the age range, sex and ethnic group of individuals to be tested. Also, all spirometric indices should use the same source for reference values (*i.e.* FVC and FEV_1 should not be taken from a different reference value source than the FEV_1/FVC %).

INTERPRETATION STRATEGIES

For a full account of interpretive strategies, the ATS and ERS have now revised [44] their previous statements [39, 41–43].

The interpretation of lung function tests involves two tasks: 1) the classification of the derived values with respect to a reference population and assessment of the reliability of the data; and 2) the integration of the obtained values into the diagnosis, therapy and prognosis for an individual patient.

The first task is ordinarily the responsibility of the laboratory director or his/her designee, and not only serves to communicate information to referring healthcare providers, but is also an important aspect of laboratory quality control. The second task is usually the responsibility of the physician requesting the studies and is performed within the context of patient care.

TABLE 4 List of abbreviations and meanings

ATPD	Ambient temperature, ambient pressure, and dry
ATPS	Ambient temperature and pressure saturated with water vapour
BTPS	Body temperature (*i.e.* 37℃), ambient pressure, saturated with water vapour
C	Centigrade
CFC	Chlorofluorocarbons
cm	Centimetres
COHb	Carboxyhaemoglobin
$D_{L,CO}$	Diffusing capacity for the lungs measured using carbon monoxide, also known as transfer factor
$D_{L,CO}/V_A$	Diffusing capacity for carbon monoxide per unit of alveolar volume, also known as K_{CO}
D_M	Membrane-diffusing capacity
DT	Dwell time of flow >90% of PEF
EFL	Expiratory flow limitation
ERV	Expiratory reserve volume
EV	Back extrapolated volume
EVC	Expiratory vital capacity
$F_{A,X}$	Fraction of gas X in the alveolar gas
$F_{A,X,t}$	Alveolar fraction of gas X at time t
$FEF_{25-75\%}$	Mean forced expiratory flow between 25% and 75% of FVC
$FEF_{X\%}$	Instantaneous forced expiratory flow when X% of the FVC has been expired
FEV_1	Forced expiratory volume in one second
FEV_t	Forced expiratory volume in t seconds
$F_{E,X}$	Fraction of expired gas X
$FIF_{X\%}$	Instantaneous forced inspiratory flow at the point where X% of the FVC has been expired
$F_{I,X}$	Fraction of inspired gas X
FIVC	Forced inspiratory vital capacity
FRC	Functional residual capacity
FVC	Forced vital capacity
H_2O	Water
Hb	Haemoglobin
Hg	Mercury
Hz	Hertz; cycles per second
IC	Inspiratory capacity
IVC	Inspiratory vital capacity
K_{CO}	Transfer coefficient of the lung (*i.e.* $D_{L,CO}/V_A$)
kg	Kilograms
kPa	Kilopascals
L	Litres
$L \cdot min^{-1}$	Litres per minute
$L \cdot s^{-1}$	Litres per second
lb	Pounds weight
MFVL	Maximum flow–volume loop
mg	Milligrams
mL	Millilitres
mm	Millimetres
MMEF	Maximum mid-expiratory flow
ms	Milliseconds
MVV	Maximum voluntary ventilation
P_{A,O_2}	Alveolar oxygen partial pressure
PB	Barometric pressure
PEF	Peak expiratory flow
P_{H_2O}	Water vapour partial pressure
P_{I,O_2}	Inspired oxygen partial pressure
θ (theta)	Specific uptake of CO by the blood
RT	Rise time from 10% to 90% of PEF
RV	Residual volume
s	Seconds
STPD	Standard temperature (273 K, 0℃), pressure (101.3 kPa, 760 mmHg) and dry
TB	Tuberculosis
TGV (or V_{TG})	Thoracic gas volume
t_I	Time taken for inspiration
TLC	Total lung capacity
Tr	Tracer gas
t_{tot}	Total time of respiratory cycle
V_A	Alveolar volume
$V_{A,eff}$	Effective alveolar volume
VC	Vital capacity
V_c	Pulmonary capillary blood volume
V_D	Dead space volume
V_I	Inspired volume
V_S	Volume of the expired sample gas
μg	Micrograms

It is the responsibility of the laboratory director to develop explicit procedures for the interpretation of lung function tests and to select appropriate reference values. The procedures for interpretation and choosing reference values may legitimately vary from laboratory to laboratory, depending upon geographical location and the characteristics of the population being tested. The interpretative strategy should be consistent and take into consideration the consequences of false-positive and false-negative errors. In this way, referring physicians will not infer a change in the condition of the patient from a change in interpretation when it is, in fact, the result of a change in the approach of the interpreting physician.

ABBREVIATIONS

Table 4 contains a list of abbreviations and their meanings, which will be used in this series of Task Force reports.

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Standardisation of spirometry

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BACKGROUND

Spirometry is a physiological test that measures how an individual inhales or exhales volumes of air as a function of time. The primary signal measured in spirometry may be volume or flow.

Spirometry is invaluable as a screening test of general respiratory health in the same way that blood pressure provides important information about general cardiovascular health. However, on its own, spirometry does not lead clinicians directly to an aetiological diagnosis. Some indications for spirometry are given in table 1.

In this document, the most important aspects of spirometry are the forced vital capacity (FVC), which is the volume delivered during an expiration made as forcefully and completely as possible starting from full inspiration, and the forced expiratory volume (FEV) in one second, which is the volume delivered in the first second of an FVC manoeuvre. Other spirometric variables derived from the FVC manoeuvre are also addressed.

Spirometry can be undertaken with many different types of equipment, and requires cooperation between the subject and the examiner, and the results obtained will depend on technical as well as personal factors (fig. 1). If the variability of the results can be diminished and the measurement accuracy can be improved, the range of normal values for populations can be narrowed and abnormalities more easily detected. The Snowbird workshop held in 1979 resulted in the first American Thoracic Society (ATS) statement on the standardisation of spirometry [1]. This was updated in 1987 and again in 1994 [2, 3]. A similar initiative was undertaken by the European Community for Steel and Coal, resulting in the first European standardisation document in 1983 [4]. This was then updated in 1993 as the official statement of the European Respiratory Society (ERS) [5]. There are generally only minor differences between the two most recent ATS and ERS statements, except that the ERS statement includes absolute lung volumes and the ATS does not.

This document brings the views of the ATS and ERS together in an attempt to publish standards that can be applied more

TABLE 1 Indications for spirometry

Diagnostic
To evaluate symptoms, signs or abnormal laboratory tests
To measure the effect of disease on pulmonary function
To screen individuals at risk of having pulmonary disease
To assess pre-operative risk
To assess prognosis
To assess health status before beginning strenuous physical activity programmes
Monitoring
To assess therapeutic intervention
To describe the course of diseases that affect lung function
To monitor people exposed to injurious agents
To monitor for adverse reactions to drugs with known pulmonary toxicity
Disability/impairment evaluations
To assess patients as part of a rehabilitation programme
To assess risks as part of an insurance evaluation
To assess individuals for legal reasons
Public health
Epidemiological surveys
Derivation of reference equations
Clinical research

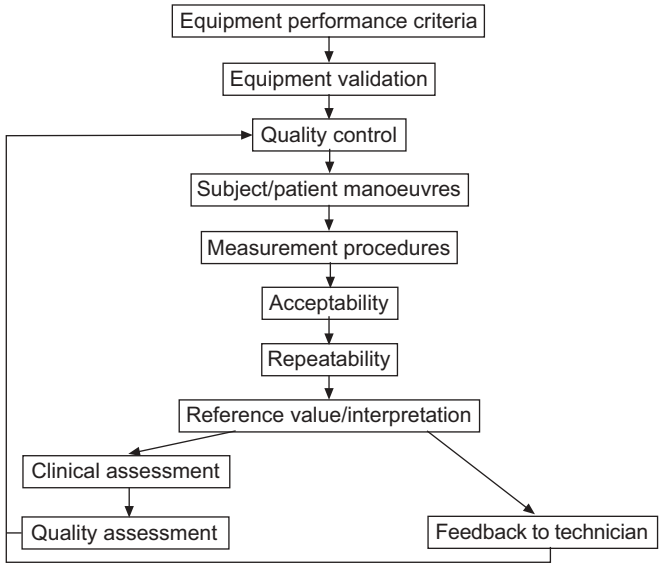

FIGURE 1. Spirometry standardisation steps.

widely. The statement is structured to cover definitions, equipment and patient-related procedures. All recording devices covered by this statement must meet the relevant requirements, regardless of whether they are for monitoring or diagnostic purposes. There is no separate category for ''monitoring'' devices.

Although manufacturers have the responsibility for producing pulmonary function testing systems that satisfy all the recommendations presented here, it is possible that, for some equipment, meeting all of them may not always be achievable. In these circumstances, manufacturers should clearly identify which equipment requirements have not been met. While manufacturers are responsible for demonstrating the accuracy and reliability of the systems that they sell, it is the user who is responsible for ensuring that the equipment's measurements remain accurate. The user is also responsible for following local law, which may have additional requirements. Finally, these guidelines are minimum guidelines, which may not be sufficient for all settings, such as when conducting research, epidemiological studies, longitudinal evaluations and occupational surveillance.

FEV_1 AND FVC MANOEUVRE

Definitions

FVC is the maximal volume of air exhaled with maximally forced effort from a maximal inspiration, *i.e.* vital capacity performed with a maximally forced expiratory effort, expressed in litres at body temperature and ambient pressure saturated with water vapour (BTPS; see *BTPS correction* section).

FEV_1 is the maximal volume of air exhaled in the first second of a forced expiration from a position of full inspiration, expressed in litres at BTPS.

Equipment

Requirements

The spirometer must be capable of accumulating volume for $\geqslant$15 s (longer times are recommended) and measuring volumes of $\geqslant$8 L (BTPS) with an accuracy of at least $\pm$3% of reading or $\pm$0.050 L, whichever is greater, with flows between 0 and 14 $L \cdot s^{-1}$. The total resistance to airflow at 14.0 $L \cdot s^{-1}$ must be $<$1.5 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.15 $kPa \cdot L^{-1} \cdot s^{-1}$; see *Minimal recommendations for spirometry systems* section). The total resistance must be measured with any tubing, valves, pre-filter, *etc*. included that may be inserted between the subject and the spirometer. Some devices may exhibit changes in resistance due to water vapour condensation, and accuracy requirements must be met under BTPS conditions for up to eight successive FVC manoeuvres performed in a 10-min period without inspiration from the instrument.

Display

For optimal quality control, both flow–volume and volume–time displays are useful, and test operators should visually inspect the performance of each manoeuvre for quality assurance before proceeding with another manoeuvre. This inspection requires tracings to meet the minimum size and resolution requirements set forth in this standard.

Displays of flow *versus* volume provide more detail for the initial portion (first 1 s) of the FVC manoeuvre. Since this portion of the manoeuvre, particularly the peak expiratory flow (PEF), is correlated with the pleural pressure during the manoeuvre, the flow–volume display is useful to assess the magnitude of effort during the initial portions of the manoeuvre. The ability to overlay a series of flow–volume curves registered at the point of maximal inhalation may be helpful in evaluating repeatability and detecting submaximal efforts. However, if the point of maximal inhalation varies between blows, then the interpretation of these results is difficult because the flows at identical measured volumes are being achieved at different absolute lung volumes. In contrast, display of the FVC manoeuvre as a volume–time graph provides more detail for the latter part of the manoeuvre. A volume–time tracing of sufficient size also allows independent measurement and calculation of parameters from the FVC manoeuvres. In a display of multiple trials, the sequencing of the blows should be apparent to the user.

For the start of test display, the volume–time display should include $\geqslant$0.25 s, and preferably 1 s, before exhalation starts (zero volume). This time period before there is any change in volume is needed to calculate the back extrapolated volume (EV; see *Start of test criteria* section) and to evaluate effort during the initial portion of the manoeuvre. Time zero, as defined by EV, must be presented as the zero point on the graphical output.

The last 2 s of the manoeuvre should be displayed to indicate a satisfactory end of test (see *End of test criteria* section).

When a volume–time curve is plotted as hardcopy, the volume scale must be $\geqslant$10 $mm \cdot L^{-1}$ (BTPS). For a screen display, 5 $mm \cdot L^{-1}$ is satisfactory (table 2).

The time scale should be $\geqslant$20 $mm \cdot s^{-1}$, and larger time scales are preferred ($\geqslant$30 $mm \cdot s^{-1}$) when manual measurements are made [1, 6, 7]. When the volume–time plot is used in conjunction with a flow–volume curve (*i.e.* both display methods are provided for interpretations and no hand

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 required	Scale factor
Volume#	0.050 L	5 mm·L^{-1}	0.025 L	10 mm·L^{-1}
Flow#	0.200 L·s^{-1}	2.5 mm·L^{-1}·s^{-1}	0.100 L·s^{-1}	5 mm·L^{-1}·s^{-1}
Time	0.2 s	10 mm·s^{-1}	0.2 s	20 mm·s^{-1}

#: 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 linearity	Quarterly	1-L increments with a calibrating syringe measured over entire volume range
Flow linearity	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

measurements are performed), the time scale requirement is reduced to 10 mm·s^{-1} from the usually required minimum of 20 mm·s^{-1} (table 2). The rationale for this exception is that the flow–volume curve can provide the means for quality assessment during the initial portion of the FVC manoeuvre. The volume–time curve can be used to evaluate the latter part of the FVC manoeuvre, making the time scale less critical.

Validation

It is strongly recommended that spirometry systems should be evaluated using a computer-driven mechanical syringe or its equivalent, in order to test the range of exhalations that are likely to be encountered in the test population. Testing the performance of equipment is not part of the usual laboratory procedures (see *Test signals for spirometer testing* section).

Quality control

Attention to equipment quality control and calibration is an important part of good laboratory practice. At a minimum, the requirements are as follows: 1) a log of calibration results is maintained; 2) the documentation of repairs or other alterations which return the equipment to acceptable operation; 3) the dates of computer software and hardware updates or changes; and 4) if equipment is changed or relocated (*e.g.* industrial surveys), calibration checks and quality-control procedures must be repeated before further testing begins.

Key aspects of equipment quality control are summarised in table 3.

Calibration is the procedure for establishing the relationship between sensor-determined values of flow or volume and the actual flow or volume.

A calibration check is different from calibration and is the procedure used to validate that the device is within calibration limits, *e.g.* ±3% of true. If a device fails its calibration check, then a new calibration procedure or equipment maintenance is required. Calibration checks must be undertaken daily, or more frequently, if specified by the manufacturer.

The syringe used to check the volume calibration of spirometers must have an accuracy of ±15 mL or ±0.5% of the full scale (15 mL for a 3-L syringe), and the manufacturer must provide recommendations concerning appropriate intervals between syringe calibration checks. Users should be aware that a syringe with an adjustable or variable stop may be out of calibration if the stop is reset or accidentally moved. Calibration syringes should be periodically (*e.g.* monthly) leak tested at more than one volume up to their maximum; this can be done by attempting to empty them with the outlet corked. A dropped or damaged syringe should be considered out of calibration until it is checked.

With regard to time, assessing mechanical recorder time scale accuracy with a stopwatch must be performed at least quarterly. An accuracy of within 2% must be achieved.

Quality control for volume-measuring devices

The volume accuracy of the spirometer must be checked at least daily, with a single discharge of a 3-L calibrated syringe. Daily calibration checking is highly recommended so that the onset of a problem can be determined within 1 day, and also to help define day-to-day laboratory variability. More frequent checks may be required in special circumstances, such as: 1) during industrial surveys or other studies in which a large number of subject manoeuvres are carried out, the equipment's calibration should be checked more frequently than daily [8]; and 2) when the ambient temperature is changing (*e.g.* field studies), volume accuracy must be checked more frequently than daily and the BTPS correction factor appropriately updated.

The accuracy of the syringe volume must be considered in determining whether the measured volume is within acceptable limits. For example, if the syringe has an accuracy of 0.5%, a reading of ±3.5% is appropriate.

The calibration syringe should be stored and used in such a way as to maintain the same temperature and humidity of the testing site. This is best accomplished by keeping the syringe in close proximity to the spirometer, but out of direct sunlight and away from heat sources.

Volume-type spirometer systems must be evaluated for leaks every day [9, 10]. The importance of undertaking this daily test cannot be overstressed. Leaks can be detected by applying a constant positive pressure of ⩾3.0 cmH_2O (0.3 kPa) with the spirometer outlet occluded (preferably at or including the mouthpiece). Any observed volume loss >30 mL after 1 min indicates a leak [9, 10] and needs to be corrected.

At least quarterly, volume spirometers must have their calibration checked over their entire volume range using a calibrated syringe [11] or an equivalent volume standard. The measured volume should be within ±3.5% of the reading or 65 mL, whichever is greater. This limit includes the 0.5% accuracy limit for a 3-L syringe. The linearity check procedure provided by the manufacturer can be used if it is equivalent to one of the following procedures: 1) consecutive injections of 1-L volume increments while comparing observed volume with the corresponding cumulative measured volume, *e.g.* 0–1, 1–2, 2–3,…6–7 and 7–8 L, for an 8-L spirometer; and 2) injection of a 3-L volume starting at a minimal spirometer volume, then repeating this with a 1-L increment in the start position, *e.g.* 0–3, 1–4, 2–5, 3–6, 4–7 and 5–8 L, for an 8-L spirometer.

The linearity check is considered acceptable if the spirometer meets the volume accuracy requirements for all volumes tested.

Quality control for flow-measuring devices

With regards to volume accuracy, calibration checks must be undertaken at least daily, using a 3-L syringe discharged at least three times to give a range of flows varying between 0.5 and 12 $L \cdot s^{-1}$ (with 3-L injection times of ~6 s and <0.5 s). The volume at each flow should meet the accuracy requirement of ±3.5%. For devices using disposable flow sensors, a new sensor from the supply used for patient tests should be tested each day.

For linearity, a volume calibration check should be performed weekly with a 3-L syringe to deliver three relatively constant flows at a low flow, then three at a mid-range flow and finally three at a high flow. The volumes achieved at each of these flows should each meet the accuracy requirement of ±3.5%.

Test procedure

There are three distinct phases to the FVC manoeuvre, as follows: 1) maximal inspiration; 2) a ''blast'' of exhalation; and 3) continued complete exhalation to the end of test (EOT).

The technician should demonstrate the appropriate technique and follow the procedure described in table 4. The subject should inhale rapidly and completely from functional residual capacity (FRC), the breathing tube should be inserted into the subject's mouth (if this has not already been done), making sure the lips are sealed around the mouthpiece and that the tongue does not occlude it, and then the FVC manoeuvre should be begun with minimal hesitation. Reductions in PEF and FEV_1 have been shown when inspiration is slow and/or there is a 4–6 s pause at total lung capacity (TLC) before beginning exhalation [12]. It is, therefore, important that the preceding inspiration is fast and any pause at full inspiration be minimal (*i.e.* only for 1–2 s). The test assumes a full inhalation before beginning the forced exhalation, and it is imperative that the subject takes a complete inhalation before beginning the manoeuvre. The subject should be prompted to ''blast,'' not just ''blow,'' the air from their lungs, and then he/she should be encouraged to fully exhale. Throughout the manoeuvre, enthusiastic coaching of the subject using appropriate body language and phrases, such as ''keep going'', is required. It is particularly helpful to observe the subject with occasional glances to check for distress, and to observe the tracing or computer display during the test to help ensure maximal effort. If the patient feels ''dizzy'', the manoeuvre should be stopped, since syncope could follow due to prolonged interruption of venous return to the thorax. This is more likely to occur in older subjects and those with airflow limitation. Performing a vital capacity (VC) manoeuvre (see *VC and IC manoeuvre* section), instead of obtaining FVC, may help to avoid syncope in some subjects. Reducing the effort partway through the manoeuvre [13] may give a higher expiratory volume in some subjects, but then is no longer a maximally forced expiration. Well-fitting false teeth should not be routinely removed, since they preserve oropharyngeal geometry and spirometry results are generally better with them in place [14].

With appropriate coaching, children as young as 5 yrs of age are often able to perform acceptable spirometry [15]. The technicians who are involved in the pulmonary function testing of children should be specifically trained to deal with such a situation. A bright, pleasant atmosphere,

TABLE 4 Procedures for recording forced vital capacity

Check the spirometer calibration
Explain the test
Prepare the subject
Ask about smoking, recent illness, medication use, *etc*.
Measure weight and height without shoes
Wash hands
Instruct and demonstrate the test to the subject, to include
Correct posture with head slightly elevated
Inhale rapidly and completely
Position of the mouthpiece (open circuit)
Exhale with maximal force
Perform manoeuvre (closed circuit method)
Have subject assume the correct posture
Attach nose clip, place mouthpiece in mouth and close lips around the mouthpiece
Inhale completely and rapidly with a pause of <1 s at TLC
Exhale maximally until no more air can be expelled while maintaining an upright posture
Repeat instructions as necessary, coaching vigorously
Repeat for a minimum of three manoeuvres; no more than eight are usually required
Check test repeatability and perform more manoeuvres as necessary
Perform manoeuvre (open circuit method)
Have subject assume the correct posture
Attach nose clip
Inhale completely and rapidly with a pause of <1 s at TLC
Place mouthpiece in mouth and close lips around the mouthpiece
Exhale maximally until no more air can be expelled while maintaining an upright posture
Repeat instructions as necessary, coaching vigorously
Repeat for a minimum of three manoeuvres; no more than eight are usually required
Check test repeatability and perform more manoeuvres as necessary

TLC: total lung capacity.

including age-appropriate toys, reading material and art, is important in making children feel at ease. Encouragement, detailed but simple instructions, lack of intimidation and visual feedback in the teaching are important in helping children to perform the manoeuvre. Even if unsuccessful at the first session, children will learn to be less intimidated and may perform far better in a subsequent session. Testing children in ''adult'' laboratories, where no effort is made to cater for the specific needs of the younger subjects, is to be discouraged.

The use of a nose clip or manual occlusion of the nares is recommended, and, for safety reasons, testing should be preferably done in the sitting position, using a chair with arms and without wheels. If testing is undertaken with the patient standing or in another position, this must be documented on the report.

Within-manoeuvre evaluation

Start of test criteria

The start of test, for the purpose of timing, is determined by the back extrapolation method (fig. 2) [1, 3, 9, 16]. The new ''time zero'' from back extrapolation defines the start for all timed measurements. For manual measurements, the back extrapolation method traces back from the steepest slope on the volume–time curve [17]. For computerised back extrapolation, it is recommended that the largest slope averaged over an 80-ms period is used [18]. Figure 2 provides an example and explanation of back extrapolation and the derivation of EV. To achieve an accurate time zero and assure the FEV_1 comes from a maximal effort curve, the EV must be <5% of the FVC or 0.150 L, whichever is greater. If a manoeuvre has an obviously hesitant start, the technician may terminate the trial early to avoid an unnecessary prolonged effort.

Rapid computerised feedback to the technician when the start criteria are not met is strongly encouraged. In addition to the expiratory manoeuvre, the volume-time curve display (graph) should ideally include the whole preceding inspiratory manoeuvre, but must include $\geq$0.25 s and preferably $\geq$1 s prior to the start of exhalation (time zero). The equipment should display the EV value. Inspection of the flow–volume curve may be added as a measure of the satisfactory start of test. PEF should be achieved with a sharp rise and occur close to the point of maximal inflation, *i.e.* the start of exhalation (see *Equipment* section).

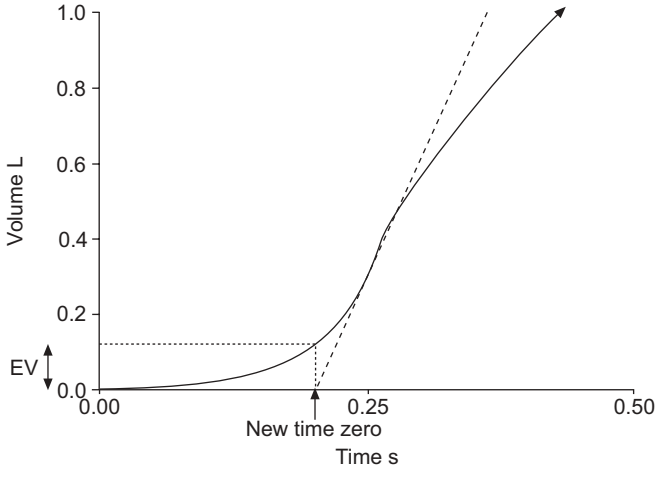

FIGURE 2. Expanded version of the early part of a subject's volume–time spirogram, illustrating back extrapolation through the steepest part of the curve, where flow is peak expiratory flow (PEF), to determine the new ''time zero''. Forced vital capacity (FVC)=4.291 L; back extrapolated volume (EV)=0.123 L (2.9% FVC). -----: back extrapolation line through PEF.

End of test criteria

It is important for subjects to be verbally encouraged to continue to exhale the air at the end of the manoeuvre to obtain optimal effort, *e.g.* by saying ''keep going''. EOT criteria are used to identify a reasonable FVC effort, and there are two recommended EOT criteria, as follows. 1) The subject cannot or should not continue further exhalation. Although subjects should be encouraged to achieve their maximal effort, they should be allowed to terminate the manoeuvre on their own at any time, especially if they are experiencing discomfort. The technician should also be alert to any indication that the patient is experiencing discomfort, and should terminate the test if a patient is becoming uncomfortable or is approaching syncope. 2) The volume–time curve shows no change in volume (<0.025 L) for $\geq$1 s, and the subject has tried to exhale for $\geq$3 s in children aged <10 yrs and for $\geq$6 s in subjects aged >10 yrs.

The equipment should signal to the technician if the plateau criteria were not met. A satisfactory EOT may still have been achieved, but an equipment alert will help the technician to pinpoint where the subject may need more encouragement. It is of note that a closure of the glottis may prematurely terminate a manoeuvre at <6 s, even when the apparent duration of the blow exceeds 6 s.

For patients with airways obstruction or older subjects, exhalation times of >6 s are frequently needed. However, exhalation times of >15 s will rarely change clinical decisions. Multiple prolonged exhalations are seldom justified and may cause light headedness, syncope, undue fatigue and unnecessary discomfort.

Achieving EOT criteria is one measure of manoeuvre acceptability. Manoeuvres that do not meet EOT criteria should not be used to satisfy the requirement of three acceptable manoeuvres. However, early termination, by itself, is not a reason to eliminate all the results from such a manoeuvre from further consideration. Information such as the FEV_1 may be useful (depending on the length of exhalation) and can be reported from these early terminated manoeuvres.

Some young children may have difficulty meeting the ATS EOT criteria [3], although they may meet other repeatability criteria [19]. Curve-fitting techniques [20] may prove useful in developing new EOT criteria specific for young children.

Additional criteria

A cough during the first second of the manoeuvre can affect the measured FEV_1 value. Coughing in the first second or any other cough that, in the technician's judgment, interferes with the measurement of accurate results [3] will render a test unacceptable.

A Valsalva manoeuvre (glottis closure) or hesitation during the manoeuvre that causes a cessation of airflow in a manner that precludes an accurate estimate of either FEV1 or FVC [3] will render a test unacceptable.

There must be no leak at the mouth [3]. Patients with neuromuscular disease may require manual or other assistance from the technician to guarantee an adequate seal.

Obstruction of the mouthpiece, *e.g.* by the tongue being placed in front of the mouthpiece or by teeth in front of the mouthpiece, or by distortion from biting, may affect the performance of either the device or the subject.

Summary of acceptable blow criteria

The acceptability criteria are a satisfactory start of test and a satisfactory EOT, *i.e.* a plateau in the volume–time curve. In addition, the technician should observe that the subject understood the instructions and performed the manoeuvre with a maximum inspiration, a good start, a smooth continuous exhalation and maximal effort. The following conditions must also be met: 1) without an unsatisfactory start of expiration, characterised by excessive hesitation or false start extrapolated volume or EV >5% of FVC or 0.150 L, whichever is greater (fig. 2); 2) without coughing during the first second of the manoeuvre, thereby affecting the measured FEV1 value, or any other cough that, in the technician's judgment, interferes with the measurement of accurate results [3]; 3) without early termination of expiration (see *End of test criteria* section); 4) without a Valsalva manoeuvre (glottis closure) or hesitation during the manoeuvre that causes a cessation of airflow, which precludes accurate measurement of FEV1 or FVC [3]; 5) without a leak [3]; 6) without an obstructed mouthpiece (*e.g.* obstruction due to the tongue being placed in front of the mouthpiece, or teeth in front of the mouthpiece, or mouthpiece deformation due to biting); and 7) without evidence of an extra breath being taken during the manoeuvre.

It should be noted that a usable curve must only meet conditions 1 and 2 above, while an acceptable curve must meet all of the above seven conditions.

It is desirable to use a computer-based system that provides feedback to the technician when the above conditions are not met. The reporting format should include qualifiers indicating the acceptability of each manoeuvre. However, failure to meet these goals should not necessarily prevent reporting of results, since, for some subjects, this is their best performance. Records of such manoeuvres should be retained since they may contain useful information.

Between-manoeuvre evaluation

Using the previously described criteria, an adequate test requires a minimum of three acceptable FVC manoeuvres. Acceptable repeatability is achieved when the difference between the largest and the next largest FVC is ⩽0.150 L and the difference between the largest and next largest FEV1 is ⩽0.150 L [21]. For those with an FVC of ⩽1.0 L, both these values are 0.100 L. If these criteria are not met in three manoeuvres, additional trials should be attempted, up to, but usually no more than, eight manoeuvres. Large variability among tests is often due to incomplete inhalations. Some patients may require a brief rest period between manoeuvres. Volume–time or flow–volume curves from at least the best three FVC manoeuvres must be retained. Table 5 gives a summary of the within- and between-manoeuvre evaluation.

Manoeuvre repeatability

For FVC measurements, acceptability must be determined by ascertaining that the recommendations outlined previously on performing the FVC test are met. The guidelines of the ATS [3] contain examples of unacceptable volume–time and corresponding flow–volume curves. Figure 3 shows a flow chart outlining how the criteria for blow acceptability are applied before those for repeatability.

The repeatability criteria are used to determine when more than three acceptable FVC manoeuvres are needed; these criteria are not to be used to exclude results from reports or to exclude subjects from a study. Labelling results as being derived from data that do not conform to the repeatability criteria described previously is recommended. In addition, the repeatability criteria are minimum requirements. Many subjects are able to achieve FVC and FEV1 repeatability to within 0.150 L. Manoeuvres with an unacceptable start of test or a cough (unusable curve) must be discarded before applying the repeatability criteria and cannot be used in determining the best values. Manoeuvres with early termination or a Valsalva manoeuvre may be used for selecting the largest FVC and FEV1.

TABLE 5 Summary of within- and between-manoeuvre acceptability criteria

Within-manoeuvre criteria
Individual spirograms are ''acceptable'' if
They are free from artefacts [3]
Cough during the first second of exhalation
Glottis closure that influences the measurement
Early termination or cut-off
Effort that is not maximal throughout
Leak
Obstructed mouthpiece
They have good starts
Extrapolated volume <5% of FVC or 0.15 L, whichever is greater
They show satisfactory exhalation
Duration of ⩾6 s (3 s for children) or a plateau in the volume–time curve or
If the subject cannot or should not continue to exhale
Between-manoeuvre criteria
After three acceptable spirograms have been obtained, apply the following tests
The two largest values of FVC must be within 0.150 L of each other
The two largest values of FEV1 must be within 0.150 L of each other
If both of these criteria are met, the test session may be concluded
If both of these criteria are not met, continue testing until
Both of the criteria are met with analysis of additional acceptable spirograms
or
A total of eight tests have been performed (optional) or
The patient/subject cannot or should not continue
Save, as a minimum, the three satisfactory manoeuvres

FVC: forced vital capacity; FEV1: forced expiratory volume in one second.

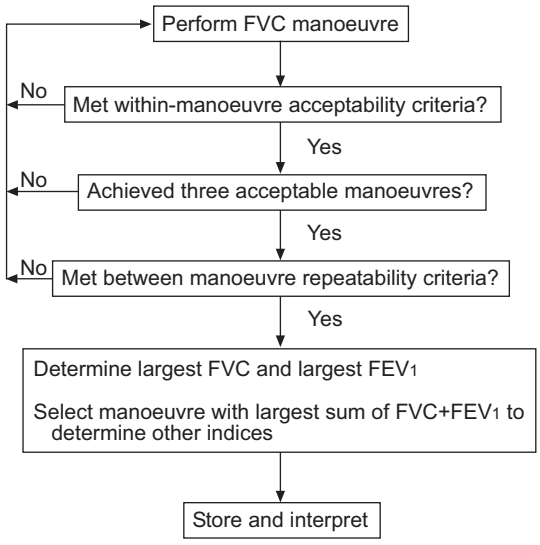

FIGURE 3. Flow chart outlining how acceptability and reapeatability criteria are to be applied. FVC: forced vital capacity; FEV_1: forced expiratory volume in one second.

No spirogram or test result should be rejected solely on the basis of its poor repeatability. The repeatability of results should be considered at the time of interpretation. The use of data from manoeuvres with poor repeatability or failure to meet the EOT requirements is left to the discretion of the interpreter.

Maximum number of manoeuvres

Although there may be some circumstances in which more than eight consecutive FVC manoeuvres may be needed, eight is generally a practical upper limit for most subjects [22, 23]. After several forced expiratory manoeuvres, fatigue can begin to take its toll on subjects and additional manoeuvres would be of little added value. In extremely rare circumstances, subjects may show a progressive reduction in FEV_1 or FVC with each subsequent blow. If the cumulative drop exceeds 20% of start value, the test procedure should be terminated in the interest of patient safety. The sequence of the manoeuvres should be recorded.

Test result selection

FVC and FEV_1 should be measured from a series of at least three forced expiratory curves that have an acceptable start of test and are free from artefact, such as a cough (*i.e.* ''usable curves''). The largest FVC and the largest FEV_1 (BTPS) should be recorded after examining the data from all of the usable curves, even if they do not come from the same curve.

Other derived indices

FEV_t

FEV_t is the maximal volume exhaled by time t seconds (timed from the time zero defined by back extrapolation) of a forced expiration from a position of full inspiration, expressed in litres at BTPS. Very young children may not be able to produce prolonged expirations, but there is increasing evidence that indices derived from blows with forced expiratory times of <1 s may have clinical usefulness [19]. At present, there are insufficient data to recommend the use of $FEV_{0.5}$ or $FEV_{0.75}$.

When the subject does not exhale completely, the volume accumulated over a shorter period of time (*e.g.* 6 s) may be used as an approximate surrogate for FVC. When such surrogates are used, the volume label should reflect the shorter exhalation time (*e.g.* FEV_6 for a 6-s exhalation). FEV_6 has been increasingly considered a reasonably reliable surrogate for FVC [24] and can be used for normalising FEV_1 (*e.g.* FEV_1/FEV_6). Recording FEV_6 seems to have the advantage of being more reproducible than FVC, being less physically demanding for patients and providing a more explicit EOT. Confirmation from other studies is required.

Standardisation of FEV_1 for expired volume, FEV_1/FVC and FEV_1/VC

In some patients, a slow or unforced VC or inspiratory vital capacity (IVC) manoeuvre (see *VC and IC manoeuvre* section) may provide a larger and more appropriate denominator for calculation of the FEV_1/VC%. Some investigators have reported that the VC is slightly higher than the FVC in normal subjects [25].

$FEF_{25–75\%}$

The mean forced expiratory flow between 25% and 75% of the FVC ($FEF_{25–75\%}$) has also been known as the maximum mid-expiratory flow. This index is taken from the blow with the largest sum of FEV_1 and FVC. The $FEF_{25–75\%}$ must be measured with an accuracy of at least $\pm$5% of reading or $\pm$0.200 $L \cdot s^{-1}$ whichever is greater, over a range of up to 7 $L \cdot s^{-1}$. It should be noted that it is highly dependent on the validity of the FVC measurement and the level of expiratory effort.

PEF

PEF is usually obtained from flow–volume curve data. It is the maximum expiratory flow achieved from a maximum forced expiration, starting without hesitation from the point of maximal lung inflation, expressed in $L \cdot s^{-1}$. When PEF is recorded using a patient-administered portable PEF meter, it is often expressed in $L \cdot min^{-1}$. PEF is covered in more detail later.

Maximal expiratory flow–volume loops

The shape of a maximum flow–volume loop (MFVL), which includes forced inspiratory manoeuvres, can be helpful in quality control and in detecting the presence of upper airway obstruction. None of the numerical indices from a MFVL has clinical utility superior to FEV_1, FVC, $FEF_{25–75\%}$ and PEF, and are not considered in detail here.

Definitions

With regard to instantaneous flows, the recommended measure is the instantaneous forced expiratory flow when X% of the FVC has been expired ($FEF_{X\%}$). The maximal instantaneous forced expiratory flow when X% of the FVC remains to be expired ($MEF_{X\%}$) was the term previously recommended in Europe.

Instantaneous forced inspiratory flow when X% of the FVC has been expired ($FIF_{X\%}$) and mid-inspiratory flow when X% of the FVC has been expired refer to the flows measured on the inspiratory limb of a flow–volume loop. $FIF_{25–75\%}$, also

referred to as maximal mid-inspiratory flow, is analogous to $FEF_{25-75\%}$ (see *Other derived indices* section).

Equipment

Instantaneous flows must be measured with an accuracy of $\pm 5\%$ of reading or ± 0.200 L·s^{-1}, whichever is greater, over a range of -14–14 L·s^{-1}. The level of minimum detectable flow should be 0.025 L·s^{-1}. When a maximum flow–volume loop is plotted or displayed, exhaled flow must be plotted upwards, and exhaled volume towards the right. A 2:1 ratio must be maintained between the flow and volume scales, *e.g.* 2 L·s^{-1} of flow and 1 L of exhaled volume must be the same distance on their respective axes. The flow and volume scales, used in reviewing test performance, must be equivalent to that shown in table 2.

Test procedure

The subject has to make a full expiratory and inspiratory loop as a single manoeuvre. In many laboratories, this is the primary manoeuvre for spirometry. The subject is asked to take a rapid full inspiration to TLC from room air through the mouth, then insert the mouthpiece and, without hesitation, perform an expiration with maximum force until no more gas can be expelled, followed by a quick maximum inspiration. At this point, the manoeuvre is finished.

An alternative procedure is for the subject to insert the mouthpiece while undertaking tidal breathing at FRC, and then, in one continuous sequence, do the following: make a slow expiration to residual volume (RV); followed directly by a slow inspiration to TLC; follow this by a rapid full expiration with maximal effort to RV; and followed by a rapid full inspiration with maximal effort back to TLC.

This procedure is slightly more complicated and may not be suitable for all equipment, but it obtains a measurement of VC as well as FVC.

Within- and between-manoeuvre evaluation

These evaluations are the same as for FVC (see *Within-manoeuvre evaluation* and *Between-manoeuvre evaluation* sections). Occasionally, a subject is unable to perform a satisfactory inspiratory limb immediately following a maximal forced expiratory manoeuvre. This is particularly common in the elderly and the infirm. In these circumstances, it may be necessary for the subject to record an inspiratory manoeuvre separately from the expiratory manoeuvre. Equipment should be able to perform these separately and then present three or more loops together on a graphical display or output.

Flow–volume loop examples

The following figures (figures 4–10) give typical examples of commonly encountered flow–volume loop configurations. The advantages of visual pattern recognition from the MFVL can readily be appreciated. The shapes of the manoeuvres must be repeatable (fig. 10) for any interpretation to be made. This is especially true for the plateau effect on expiratory and inspiratory limbs of the manoeuvre found in upper airway obstruction, as this can be mimicked by poor effort, which is usually variable from blow to blow. A further explanation is given in the ATS/ERS statement on lung function interpretation [26].

Reversibility testing

A determination of airflow-limitation reversibility with drug administration is commonly undertaken as part of lung function testing. The choice of drug, dose and mode of delivery is a clinical decision depending on what the clinician wishes to learn from the test.

If the aim of the test is to determine whether the patient's lung function can be improved with therapy in addition to their regular treatment, then the subject can continue with his/her regular medication prior to the test.

If the clinician wants to determine whether there is any evidence of reversible airflow limitation, then the subject should undergo baseline function testing when not taking any drugs prior to the test. Short-acting inhaled drugs (*e.g.* the β-agonist albuterol/salbutamol or the anticholinergic agent ipratropium bromide) should not be used within 4 h of testing. Long-acting β-agonist bronchodilators (*e.g.* salmeterol or formoterol) and oral therapy with aminophylline or slow-release β-agonists should be stopped for 12 h prior to the test. Smoking should be avoided for $\geq$1 h prior to testing and throughout the duration of the test procedure.

Method

The following steps are undertaken. 1) The subject has three acceptable tests of FEV_1, FVC and PEF recorded as described previously. 2) The drug is administered in the dose and by the method indicated for the test. For example, after a gentle and incomplete expiration, a dose of 100 μg of albuterol/salbutamol is inhaled in one breath to TLC from a valved spacer device. The breath is then held for 5–10 s before the subject exhales. Four separate doses (total dose 400 μg) are delivered at ~30-s intervals. This dose ensures that the response is high on the albuterol dose–response curve. A lower dose can be used if there is concern about any effect on the patient's heart rate or tremor. Other drugs can also be used. For the anticholinergic agent ipratropium bromide, the total dose is 160 μg (4 × 40 μg).

Three additional acceptable tests are recorded $\geq$10 min and up to 15 min later for short-acting β_2-agonists, and 30 min later for short-acting anticholinergic agents.

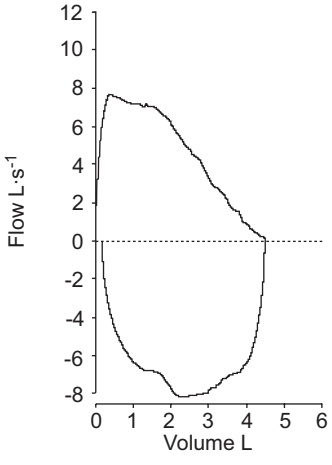

FIGURE 4. Flow–volume loop of a normal subject.

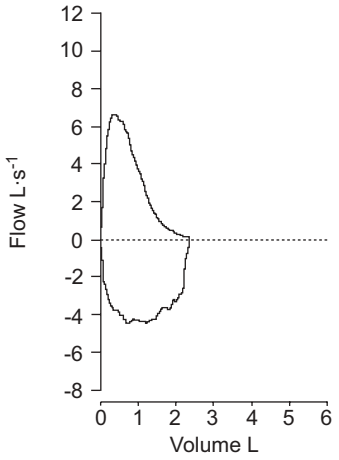

FIGURE 5. Flow–volume loop of a normal subject with end expiratory curvilinearity, which can be seen with ageing.

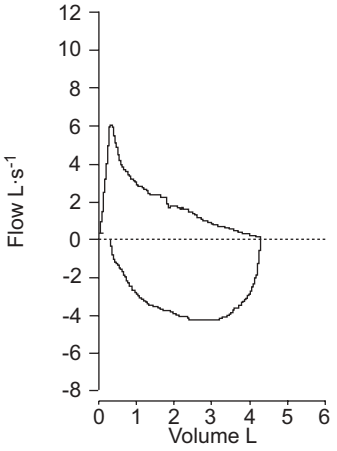

FIGURE 6. Moderate airflow limitation in a subject with asthma.

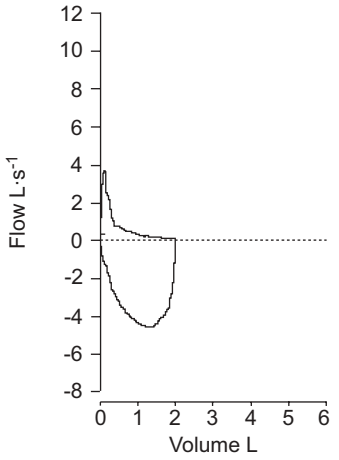

FIGURE 7. Severe airflow limitation in a subject with chronic obstructive pulmonary disease.

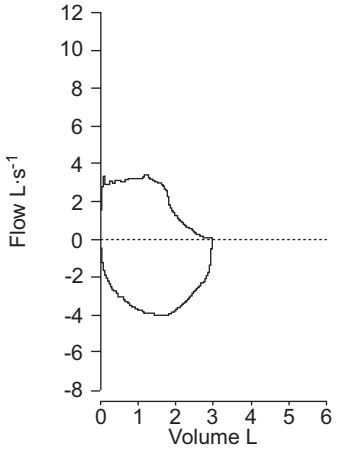

FIGURE 8. Variable intra-thoracic upper airway obstruction.

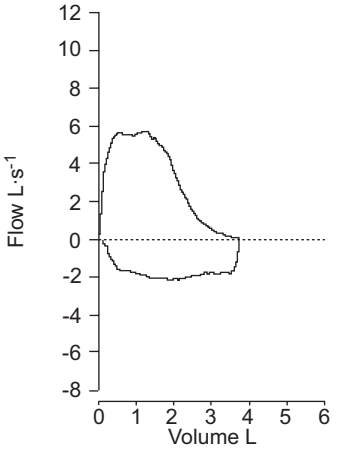

FIGURE 9. Variable extra-thoracic upper airway obstruction.

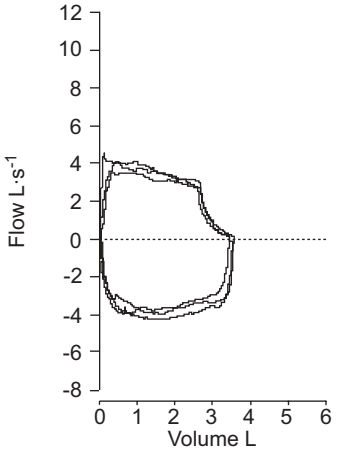

FIGURE 10. Fixed upper airway obstruction shown by three manoeuvres.

Comment on dose and delivery method

Standardising the bronchodilator dose administered is necessary in order to standardise the definition of a significant bronchodilator response. The rate of pulmonary deposition of a drug with tidal breathing from an unvented nebuliser will depend on drug concentration, rate of nebuliser output, particle-size distribution, and the ratio of the time spent in inspiration over the total respiratory time (t_i/t_{tot}) [27]. The fraction of the aerosol carried in particles with a diameter of $\leqslant 5$ μm that is expected to deposit in adult lungs if inhaled through a mouthpiece [28] is defined as the respirable fraction (RF). For example, 2.5 mg of salbutamol (albuterol) in 2.5 mL of solution, placed in a Hudson Updraft II (Hudson RCI, Temecula, CA, USA) driven by a PulmoAide compressor (De Vilbiss, Somerset, PA, USA), would produce ~0.1 mg·min^{-1} in the RF. For a respiratory rate of 15 breaths·min^{-1} and a t_i/t_{tot} of 0.45, this would give ~3 μg deposited in the lungs per breath, or 45 μg·min^{-1}. For adults using a metered dose inhaler (MDI) with a valve-holding chamber (spacer), between 10 and 20% [29, 30] of a 100-μg ''puff'' (or ~15 μg per activation) would be expected to be deposited in the lung of an adult. Without a spacer, the deposition will be less, and heavily technique dependent [31]. Pulmonary deposition from dry-powder inhalers is device specific, and breath-enhanced nebulisers deposit much more than unvented ones [32, 33]. CFC-free MDIs produce a smaller particle-size distribution and improved (up to 50% of dose) lung deposition compared with those with CFC propellant [34]. For children, pulmonary deposition is less than that in adults [35], possibly relating to the size of the upper airway. Each laboratory should be familiar with the pulmonary-deposition characteristics of the devices they use.

Determination of reversibility

This aspect is covered in detail in the interpretative strategy document of the ATS and ERS [26].

VC AND IC MANOEUVRE

Definitions

VC and IVC

The VC is the volume change at the mouth between the position of full inspiration and complete expiration, expressed in litres at BTPS. The slow VC can be derived in two ways. The expiratory vital capacity (EVC) is the maximal volume of air exhaled from the point of maximal inhalation. The IVC is the maximal volume of air inhaled from the point of maximal exhalation, achieved by a slow expiration from end-tidal inspiration. These manoeuvres are unforced, except at the point of reaching RV or TLC, respectively, where extra effort is required [36].

IC

Inspiratory capacity (IC) is volume change recorded at the mouth when taking a slow full inspiration with no hesitation, from a position of passive end-tidal expiration, *i.e.* FRC, to a position of maximum inspiration, expressed in litres at BTPS. IC is an indirect estimate of the degree of lung hyperinflation at rest, and is useful to assess changes in FRC with pharmacological interventions and physical exercise [37–41].

Equipment

For measurements of VC and IC, the spirometer or flow meter must comply with the requirements for FVC (as described previously) and be capable of accumulating volume for $\geqslant$30 s.

Expiratory manoeuvres or, ideally, both inspiratory and expiratory manoeuvres should be included in the display of VC manoeuvre. Regardless of whether the inspiratory or expiratory manoeuvre is used for deriving measurements, a display of the entire recorded VC manoeuvre must be provided. The maximal expiratory volume must be assessed to determine whether the subject has obtained a plateau in the expiratory effort. For display of the slow VC, the time scale may be reduced to 5 mm·s^{-1}.

Test procedure

VC

VC can be measured using conventional spirometers. It may also be recorded from equipment used to measure static lung volumes and their subdivisions [42]. For slow VC, a maximum of four manoeuvres is a practical upper limit. It is preferable that VC manoeuvres be performed before FVC manoeuvres because of the potential for muscular fatigue and volume history effects, where, after maximal inspiratory efforts, some patients with severe airways obstruction return to a falsely high level of FRC or RV, due to gas trapping or stress relaxation [3]. The VC manoeuvre may be considered either as an IVC, where the subject inhales completely from a position of full expiration, or as an EVC, where the subject exhales completely from a position of full inspiration. Figure 11 shows the recording of IVC and figure 12 shows an EVC recording. Important differences between inspiratory (*i.e.* IVC) and expiratory (*i.e.* EVC) manoeuvres may be observed in patients with airways obstruction [43, 44].

The test is begun by instructing the subject in the VC manoeuvre and demonstrating the appropriate technique. It is important that subjects understand they must completely fill and empty their lungs. The VC manoeuvre is performed with the subject using a mouthpiece and wearing a nose clip. The manoeuvre is not forced; it is performed in a relaxed manner, except near end-inspiration and end-expiration. The subject exhales completely to RV, then inhales to TLC, and finally exhales to RV again. The technician should encourage the subject to reach maximal inhaled and exhaled volumes with a relatively constant flow. The exhalation should not be unduly slow, as this can lead to underestimation of VC. Technicians should observe the subject carefully to ensure that his/her lips are sealed, nothing obstructs the mouthpiece, no leaks occur, and that TLC and RV are reached.

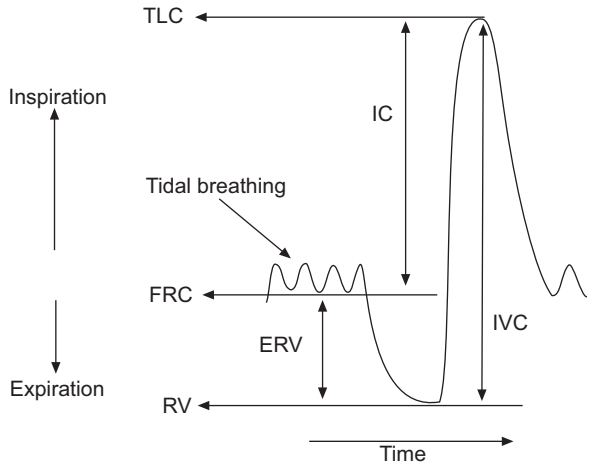

FIGURE 11. Tracing of tidal breathing followed by an expiratory manoeuvre to residual volume (RV), followed by a full inspiration to total lung capacity (TLC) to record inspiratory vital capacity (IVC) and inspiratory capacity (IC). FRC: functional residual capacity; ERV: expiratory reserve volume.

Alternatively, the subject inhales maximally, inserts the mouthpiece just past his/her front teeth, seals his/her lips around the mouthpiece, and blows slowly and evenly until there is no volume change (<0.025 L) for a 1-s period (see *End of test criteria* section). Patients with neuromuscular disease may need assistance in maintaining a tight seal at the mouth. The technician must observe the subject's inhalation to ensure

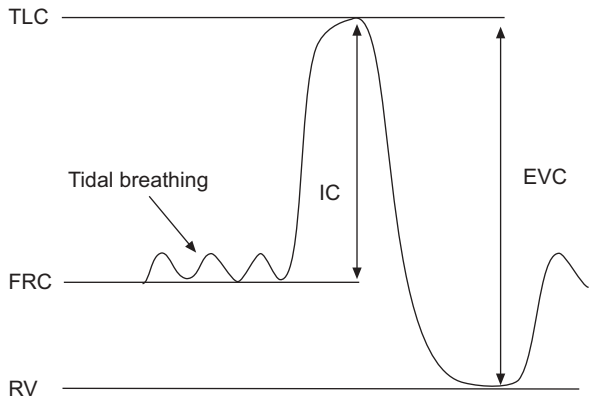

FIGURE 12. Tracing of tidal breathing followed by an inspiratory manoeuvre to total lung capacity (TLC) to record inspiratory capacity (IC), followed by a full expiration to residual volume (RV) to record expiratory reserve volume (EVC). FRC: functional residual capacity.

that it is complete, and that air is not exhaled while the mouthpiece is being inserted. The technician should assure that the expiratory manoeuvre is not forced. In healthy subjects, adequate maximal inspiratory and expiratory levels are achieved within 5–6 s.

IC

Subjects should be tested in the seated position wearing a nose clip with no air leaks between the mouth and the mouthpiece. Subjects should be relaxed (shoulders down and relaxed) and asked to breathe regularly for several breaths until the end-expiratory lung volume is stable (this usually requires at least three tidal manoeuvres). They are then urged to take a deep breath to TLC with no hesitation. Figure 12 shows a tracing from the recording of IC.

Use of a nose clip

The use of a nose clip is encouraged in VC measurements, since some people breathe through the nose when performing a slow VC manoeuvre. A nose clip must be used when performing inspiratory manoeuvres such as the IVC or IC.

Within-manoeuvre evaluation

These are the same as for FVC EOT criteria as described previously. There must be no leak at the mouth, no hesitation during the manoeuvre, and no obstruction of the mouthpiece (see *Additional criteria* section). The IC may be underestimated if the inspiratory manoeuvre is too slow due to poor effort or hesitation, or if there is premature closure of the glottis.

Between-manoeuvre evaluation

As with spirometry, a minimum of three acceptable VC manoeuvres must be obtained. If the difference in VC between the largest and next largest manoeuvre is >0.150 L, additional trials should be undertaken. Meeting repeatability criteria may require that up to, but usually no more than, four manoeuvres are performed, with a rest period of $\geq$1 min between the manoeuvres. Large variability in this test is often due to incomplete inhalations. Volume–time curves from the best two VC manoeuvres must be retained. For the IC, at least three acceptable manoeuvres should be performed. The mean coefficient of variation for IC in chronic airflow obstruction has been found to be 5 $\pm$3% [39].

Test result selection

For VC, the largest value from at least three acceptable manoeuvres should be reported. For IC, the average of at least three manoeuvres should be reported.

PEAK EXPIRATORY FLOW

Studies on the measurement of PEF are ongoing. Recent evidence has suggested that the previously applied standards may allow incorrect measurements to be made [45], and it is possible that more stringent requirements may be required. A further statement will be made when the position on the clinical significance of this is clear. However, since PEF measurements are part of asthma-management programmes, the previous recommendations [3, 46] are reiterated here.

Other instantaneous flow measurements (*e.g.* $FEF_{50\%}$, $FEF_{75\%}$) are not proven to be superior to conventional spirometric indices in a clinical setting, and, therefore, are not considered further.

Definition

PEF is the highest flow achieved from a maximum forced expiratory manoeuvre started without hesitation from a position of maximal lung inflation [46]. When it is obtained from flow–volume curve data, it is expressed at BTPS in $L \cdot s^{-1}$. The defining characteristics of the flow–time curve, in relation to PEF, are the time taken for flow to rise from 10% of PEF to 90% of PEF, *i.e.* the rise time (RT), and the duration that flow is >90% of PEF, called the dwell time (DT). When PEF is obtained with portable monitoring instruments, it is expressed in $L \cdot min^{-1}$.

Equipment

Ideally, PEF should be recorded by an instrument that primarily records flow. Measuring PEF requires an instrument that has a flat frequency response ($\pm$5%) up to 15 Hz [46]. Although there is evidence of significant frequency content in PEF up to 20 Hz [47], it is recommended, at this stage, that manufacturers achieve a goal of recording fidelity up to 15 Hz. The PEF must be measured with an accuracy of $\pm$10% or $\pm 0.3\ L \cdot s^{-1}$ ($20\ L \cdot min^{-1}$), whichever is the greater. Mean instrument resistance measured across the range of the instrument should be $<2.5\ cmH_2O \cdot L^{-1} \cdot s^{-1}$ ($0.25\ kPa \cdot L^{-1} \cdot s^{-1}$; table 6). PEF is sensitive to the resistance of the meter; for example, a resistance of $0.25\ kPa \cdot L^{-1} \cdot s^{-1}$ decreases PEF by ~8% compared with PEF measured with a low-resistance pneumotachograph [48].

Intra-instrument repeatability must be <5% or $0.150\ L \cdot s^{-1}$ ($10\ L \cdot min^{-1}$), whichever is the greater. Inter-device reproducibility must be <10% or $0.300\ L \cdot s^{-1}$ ($20\ L \cdot min^{-1}$), whichever is the greater. Calculating PEF by differentiating volume–time data may introduce noise; hence, a parabolic-fitting algorithm may be used [2] as a smoothing procedure.

Equipment validation is covered in the *Test signals for PEF meter testing* section.

Test procedure

PEF is dependent on effort and lung volume, with subject cooperation being essential. PEF must be achieved as rapidly as possible and at as high a lung volume as possible, in order to obtain the maximum value [49]. The subject must be encouraged to blow as vigorously as possible. The neck should be in a neutral position, not flexed or extended, and the subject must not cough. A nose clip is not necessary.

After the point of full lung inflation, the subject must deliver the blow without any delay. Hesitating for as little as 2 s or flexing the neck allows the tracheal visco-elastic properties to relax and PEF to drop by as much as 10% [50]. Tonguing, spitting or coughing at the start of the blow may falsely raise the recorded PEF in some devices.

In the laboratory, the subject must perform a minimum of three PEF manoeuvres. When PEF is a self-administered recording, it is important that the subject has been adequately taught how to perform the test, when to perform it and what action to take depending on the resulting value obtained. Regular checks of the patient's PEF technique and meter are an important part of the follow-up.

Within-manoeuvre evaluation

The subject must be observed to ensure a good seal at the mouth, no hesitation occurred, and there was no abnormal start to the manoeuvre.

Between-manoeuvre evaluation

The PEF values and their order must be recorded so that manoeuvre-induced bronchospasm can be detected. If the largest two out of three acceptable blows are not reproducible within 0.67 $L \cdot s^{-1}$ (40 $L \cdot min^{-1}$), up to two additional blows can be performed. Ninety-five per cent of untrained healthy subjects and patients can reproduce PEF to within 0.67 $L \cdot s^{-1}$ (40 $L \cdot min^{-1}$), and 90% to within 0.5 $L \cdot s^{-1}$ (30 $L \cdot min^{-1}$) [48]. If satisfactory repeatability has not been in achieved in five attempts, more are not likely to be helpful [51].

Test result selection

The largest value from at least three acceptable blows is recorded.

MAXIMUM VOLUNTARY VENTILATION

This test has been largely superseded by FEV_1, which was defined as the index from a single maximum forced expiratory manoeuvre that best correlated with maximum voluntary ventilation (MVV). If FEV_1 is available, then MVV has little additional contribution to make in a clinical setting. However, it may be useful in those conditions where ventilatory capacity may be impaired by mechanisms that are different from those affecting FEV_1 [26].

Definition

The MVV is the maximum volume of air a subject can breathe over a specified period of time (12 s for normal subjects). It is expressed in $L \cdot min^{-1}$ at BTPS.

Equipment

A spirometer used for measuring MVV must have an amplitude–frequency response that is flat ($\pm$10%) from zero to $\geqslant$4 Hz, at flows of up to 12 $L \cdot s^{-1}$, over the volume range. The time for exhaled volume integration or recording must be no less than 12 s and no more than 15 s [52]. The indicated time must be accurate to within $\pm$3%. The MVV must be measured with an accuracy of $\pm$10% of reading or $\pm$15 $L \cdot min^{-1}$, whichever is greater.

The evaluation of equipment is covered in the *Test signals for MVV testing* section.

Test procedure

The technician should provide proper instructions and demonstrate the manoeuvre prior to the start of testing. The subject should be tested in the sitting position wearing a nose clip. After the subject makes an airtight seal around the mouthpiece, at least three resting tidal breaths should be obtained, followed by breathing as rapidly and deeply as possible. The tongue and teeth must be positioned so as to not obstruct airflow. The technician should enthusiastically coach the subject throughout the manoeuvre, and may need to suggest faster or slower breathing to achieve an ideal rate of 90–110 $breaths \cdot min^{-1}$ [53, 54], although subjects with disease may not always achieve this rate. The technician will need to carefully observe the subject with occasional glances at the tracing to help the subject to obtain an acceptable manoeuvre. An acceptable manoeuvre should be performed with maximal effort without evidence of leakage, hesitation or measurement artefact. The subject is instructed to breathe as deeply and rapidly as possible and the tidal volume (V_T) during the manoeuvre should be greater than the subject's resting V_T.

The test interval (*e.g.* 12 s) should be reported. A rest between manoeuvres will improve subsequent efforts.

The MVV should be calculated from the sum of all individual exhalations, multiplied by the appropriate BTPS correction factor during the best 12 s of the manoeuvre. From a technical standpoint, changes in respiratory rate or V_T during the manoeuvre will influence test results.

Within-manoeuvre evaluation

In normal subjects, the goal for an acceptable MVV should be a V_T that is ~50% of the VC, with a breathing frequency that is ~90 $breaths \cdot min^{-1}$ [54]. It is unlikely that an acceptable manoeuvre will be obtained when the breathing frequency is $<$65 $breaths \cdot min^{-1}$ [54]. However, since there are little data on MVV acceptability criteria, no specific breathing frequency or volume is required. The emphasis should be on maximal effort with a goal of 90 $breaths \cdot min^{-1}$ and a volume representing ~50% of the VC. V_T during the manoeuvre is probably not as important as breathing frequency, since patients tend to breathe on the portion of the expiratory curve where air is best moved at a given frequency.

Between-manoeuvre evaluation

The subject should perform a minimum of two acceptable manoeuvres. There are no clinical studies addressing repeatability; however, additional trials should be considered when the variability between acceptable manoeuvres exceeds 20%.

Test result selection

The highest acceptable MVV ($L \cdot min^{-1}$ BTPS) and MVV rate ($breaths \cdot min^{-1}$) should be reported. An $MVV/(40 \times FEV_1)$ $<$0.80 indicates that the MVV is low relative to the FEV_1, and suggests disease or poor effort. Volume *versus* time tracings from at least two acceptable manoeuvres should be retained and available for inspection.

TECHNICAL CONSIDERATIONS

Minimal recommendations for spirometry systems

Accurate results require accurate equipment. Spirometer equipment recommendations apply to all spirometers and are minimal requirements. In some circumstances, it may be appropriate to exceed these requirements (*i.e.* in some research/surveillance applications). Instrumentation recommendations should be followed to provide accurate spirometric data and information that is comparable from laboratory to laboratory and from one time period to another [1]. The accuracy of a spirometry system depends on characteristics of the entire system, from the volume or flow transducer and the use of an in-line filter, to the recorder, display or processor. Changes in any aspect of the equipment or errors at any step in the process can affect the accuracy of the results. For example, if the BTPS correction factor is wrong, an accurately measured FVC will be incorrectly reported.

Spirometers and PEF meters are not required to measure all of the indices in table 6, but must meet the recommendations for those that are measured. Accuracy and repeatability recommendations apply over the entire volume range of the instrument.

BTPS correction

All spirometry values should be reported at BTPS by any method (measuring temperature and barometric pressure) proven effective by the manufacturer. For volume-type spirometers, the temperature inside the spirometer should be measured for each breathing manoeuvre. Regardless of the BTPS correction technique used, the ambient temperature must always be recorded with an accuracy of ±1℃. In situations where the ambient air temperature is changing rapidly (>3℃ in <30 min), continuous temperature corrections may be necessary. Spirometer users should be aware of potential problems with testing performed at lower ambient temperatures: 17℃ is the lower limit [55–63] for ambient temperature, unless a manufacturer states that their spirometer will operate accurately at lower ambient temperatures. If barometric pressure is not used in calculating the BTPS correction factor, the range of barometric pressures over which the BTPS correction factor is valid must be published by the manufacturer.

Comments

The rationale for this recommendation is based, in part, on the problems with finite cooling times of gases in volume-type spirometers [55–57] and the problems of estimating BTPS correction factors for flow devices [58–60]. When a subject performs an FVC manoeuvre, the air leaving the lungs is ~33–35℃ [61, 62] and saturated with water vapour. If the expired gas is assumed to be at BTPS, an error of ~1% will result. Most volume-type spirometers assume instantaneous cooling of the air as it enters the spirometer. This is not always the case, and FEV_t can be incorrectly reported because of it. For capillary and screen pneumotachometers, the signal depends on gas viscosity, which increases with increasing temperature. Therefore, for pneumotachometers, a different correction factor is needed for recording patients as compared with recording from the calibrating syringe. Also, correction factors will be different for inspiratory and expiratory manoeuvres. It is usually assumed that expired gas does not cool as it passes through the flow sensor. This may not be the case, particularly with unheated flow sensors [58, 59]. The error will increase if the flow sensor is located further from the mouth and more cooling occurs, as is the case when a filter is placed in front of the flow sensor. Water condensation within or on the surfaces of a flow sensor may alter its calibration.

Depending on environmental temperature, the BTPS correction factor may be as large as 10%. The method used to calculate or estimate the BTPS factor can potentially introduce significant errors; examples and a fuller explanation can be found elsewhere [3, 4].

Changes in spirometer temperature can be a source of variability. Spirometer temperature should be measured and not assumed to be constant, even over the course of one testing

TABLE 6 Range and accuracy recommendations specified for forced expiratory manoeuvres

Test	Range/accuracy (BTPS)	Flow range $L \cdot s^{-1}$	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 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.15 $kPa \cdot L^{-1} \cdot s^{-1}$)	24 ATS waveforms, 3-L Cal Syringe
FEV_1	0.5–8 L, ±3% of reading or ±0.050 L, whichever is greater	0–14	1	<1.5 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.15 $kPa \cdot L^{-1} \cdot s^{-1}$)	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 $L \cdot s^{-1}$ (20 $L \cdot min^{-1}$), whichever is greater; repeatability: ±5% of reading or ±0.15 $L \cdot s^{-1}$ (10 $L \cdot min^{-1}$), whichever is greater	0–14		Mean resistance at 200, 400, 600 $L \cdot min^{-1}$ (3.3, 6.7, 10 $L \cdot s^{-1}$) must be <2.5 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.25 $kPa \cdot L^{-1} \cdot s^{-1}$)	26 ATS flow waveforms
Instantaneous flows (except PEF)	Accuracy: ±5% of reading or ±0.200 $L \cdot s^{-1}$, whichever is greater	0–14		<1.5 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.15 $kPa \cdot L^{-1} \cdot s^{-1}$)	Data from manufacturers
$FEF_{25–75\%}$	7.0 $L \cdot s^{-1}$, ±5% of reading or ±0.200 $L \cdot s^{-1}$, whichever is greater	±14	15	Same as FEV_1	24 ATS waveforms
MVV	250 $L \cdot min^{-1}$ at V_T of 2 L within ±10% of reading or ±15 $L \cdot min^{-1}$, whichever is greater	±14 (±3%)	12–15	<1.5 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ (0.15 $kPa \cdot L^{-1} \cdot s^{-1}$)	Sine wave pump

BTPS: body temperature and ambient pressure saturated with water vapour; VC: vital capacity; FVC: forced vital capacity; ATS: American Thoracic Society; FEV_1: forced expiratory volume in one second; FEV_t: forced expiratory volume in t seconds; PEF: peak expiratory flow; $FEF_{25–75\%}$: mean forced expiratory flow between 25% and 75% of FVC; MVV: maximum voluntary ventilation; V_T: tidal volume.

session. For volume spirometers, errors up to 6% in FEV1 and FVC can occur if ambient temperature is used instead of internal spirometer temperature [64]. For volume spirometers, the temperature inside the spirometer should be measured for each breathing manoeuvre.

Test signals for spirometer testing

The diversity of FVC manoeuvres encountered in clinical practice is currently best simulated by the 24 standard volume–time waveforms developed by the ATS [3] and HANKINSON and GARDNER [65]. These waveforms can be used to drive a computer-controlled mechanical syringe, or its equivalent, for testing actual hardware and software [66, 67], or, when put in a digital form, they can evaluate only the software. Computer-controlled mechanical syringes (*i.e.* pump systems) used for validation should be accurate within $\pm$50 mL, which is 0.5% of their full range up to 10 L for FVC and FEV1. Pump systems may have accuracy values better than this for many profiles, but reproduce less accurately those test profiles with short DTs and RTs to peak flow [68, 69]. The ATS spirometry statement [3] shows the measured values for each of the 24 standard waveforms. On request, the ATS can provide these waveforms in an electronic format. Appropriate corrections for using gas at the ambient temperature and humidity instead of BTPS may need to be made for some mechanical syringe–spirometer combinations.

Method

A production spirometer is connected to the pump system for testing, orientated as it would be to test human subjects. Connecting tubing must be kept to the minimum (<0.300 L) and must not be distensible. If an in-line filter is required for testing human subjects, one must be included when the instrument is tested. Each of the 24 ATS waveforms is discharged into the spirometer five times under ambient conditions, and all of the readings are recorded.

BTPS conditions are simulated by discharging waveforms 1–4 to the spirometer three times, using air heated to 37$\pm$1°C and at >98% relative humidity. The time between each of the three tests should be <2 min.

Accuracy test

The average of the five tests under ambient conditions is compared with the standard value in the following way:

$$\text{Deviation} = \text{average} - \text{standard} \quad (1)$$

$$\text{Percentage deviation} = 100 \times (\text{average} - \text{standard})/\text{standard} \quad (2)$$

The accuracy validation limits for volumes, which include the waveform-generator inaccuracy, are $\pm$3.5% of reading or $\pm$0.100 L, whichever is greater. An accuracy error occurs if the deviation (for volumes <2.857 L) or percentage deviation (for volumes >2.857 L) exceed these limits. These limits include the allowable inaccuracy of the pump system.

Acceptable spirometer performance is defined as fewer than three accuracy errors for either FVC or FEV1 across the 24 waveforms (<5% error rate).

The average FVC and FEV1 values of the three tests simulating BTPS conditions are compared with the standard values. The validation limits for these tests under BTPS conditions are $\pm$4.5% or 0.200 L, whichever is the greater, and these limits include the allowable inaccuracy for the pump system.

Acceptable spirometer performance under BTPS conditions is defined as the accuracy requirement being met for all of the four profiles used.

Repeatability test

The FEV1 and FVC data from the accuracy test are used to derive the span of the five recordings:

$$\text{Span} = \text{maximum} - \text{minimum} \quad (3)$$

$$\text{Percentage span} = 100 \times \text{span}/\text{average} \quad (4)$$

The repeatability validation limits for the volume measured at ambient conditions are $\pm$3.5% or $\pm$0.100 L, whichever is the greater, and, for BTPS conditions, $\pm$4.5% or $\pm$0.200 L, whichever is the greater. A repeatability error occurs if the span (for volumes <2.857 L at ambient or 4.444 L at BTPS) or percentage span (for volumes above this) exceeds these limits.

Acceptable spirometer performance for repeatability under ambient conditions is defined as fewer than three accuracy errors for either FVC or FEV1 across the 24 profiles (<5% error rate). For BTPS conditions, the acceptable spirometer performance for repeatability is defined as the accuracy requirement being met for all of the four profiles.

Test signals for PEF meter testing

The 26 flow–time ATS waveforms were chosen to represent a range of PEF profiles suitable for delivery by mechanical syringe or pump systems to test PEF meters [3]. The range of profiles and method of delivery may need to be revised, as research on PEF measurement continues [45]. The mechanical syringe or suitable pump system used to validate PEF measuring equipment must have an accuracy of $\pm$2% in delivering PEF. Pump systems may have difficulty meeting this accuracy standard for profiles more demanding than the set of 26 [68, 69]. Recent evidence suggests that the frequency content in the first second of the blow that contributes to PEF is higher [47] than previously determined [70, 71]. The 26 waveforms may not cover the range of RT and DT found in ~25% of the client population [72], and, hence, more demanding test profiles may be required in future [45].

Method

Two randomly chosen production models of the flow meters should each have the 26 waveforms delivered to them five times under ambient conditions and the readings recorded. Any waveforms with a PEF outside the meter's stated operational range would not be included in the testing sequence. Appropriate correction factors for testing under ambient conditions should be applied as recommended by the manufacturer.

Accuracy test

The average reading for each of the two meters is compared with the standard, as for volumes.

The accuracy validation limits are $\pm$12% or $\pm$25 L·min^{-1}, whichever is the larger, and these limits include the 2% inaccuracy limit for the waveform generator. An accuracy error

for a given meter and given waveform occurs if the deviation and percentage deviation exceed these limits.

Acceptable performance is defined as fewer than three accuracy errors out of the total of 52 tests (26 waveforms, two meters).

Repeatability test

Flow waveforms 1, 4, 8 and 25 are discharged three times to each of 10 production meters. The repeatability validation limits are $\pm 6\%$ or ± 15 L·min^{-1}, whichever is the greater, and these limits include 1% for waveform-generator variability. A repeatability error occurs if the span and percentage span exceed these limits.

Acceptable performance is defined as six or fewer errors in the 120 tests (*i.e.* maximum error rate of 5%).

Test signals for MVV testing

A spirometry system used to measure MVV should be tested under ambient conditions with a pump producing a sinusoidal waveform, with stroke volumes up to 2 L using the four patterns of delivery previously specified [3]. Testing at BTPS is not required, and each pattern is tested twice. The accuracy validation limits of the spirometer used for measuring MVV with flows up to 250 L·min^{-1} are $\pm 10.5\%$ of reading or ± 20 L·min^{-1}, whichever is greater. The pressure at the mouthpiece must not exceed ± 10 cmH_2O (1 kPa) at any point during MVV testing. These requirements apply to volume spirometers throughout their volume range.

Acceptable performance is defined as no errors in the eight tests (four patterns, twice).

ABBREVIATIONS

Table 7 contains a list of abbreviations and their meanings, which will be used in this series of Task Force reports.

TABLE 7 List of abbreviations and meanings

ATPD	Ambient temperature, ambient pressure, and dry
ATPS	Ambient temperature and pressure saturated with water vapour
BTPS	Body temperature (*i.e.* 37℃), ambient pressure, saturated with water vapour
C	Centigrade
CFC	Chlorofluorocarbons
cm	Centimetres
COHb	Carboxyhaemoglobin
$D_{L,CO}$	Diffusing capacity for the lungs measured using carbon monoxide, also known as transfer factor
$D_{L,CO}/V_A$	Diffusing capacity for carbon monoxide per unit of alveolar volume, also known as K_{CO}
D_M	Membrane-diffusing capacity
DT	Dwell time of flow >90% of PEF
EFL	Expiratory flow limitation
ERV	Expiratory reserve volume
EV	Back extrapolated volume
EVC	Expiratory vital capacity
$F_{A,X}$	Fraction of gas X in the alveolar gas
$F_{A,X,t}$	Alveolar fraction of gas X at time t
$FEF_{25-75\%}$	Mean forced expiratory flow between 25% and 75% of FVC
$FEF_{X\%}$	Instantaneous forced expiratory flow when X% of the FVC has been expired
FEV_1	Forced expiratory volume in one second
FEV_t	Forced expiratory volume in t seconds
$F_{E,X}$	Fraction of expired gas X
$FIF_{X\%}$	Instantaneous forced inspiratory flow at the point where X% of the FVC has been inspired
$F_{I,X}$	Fraction of inspired gas X
FIVC	Forced inspiratory vital capacity
FRC	Functional residual capacity
FVC	Forced vital capacity
H_2O	Water
Hb	Haemoglobin
Hg	Mercury
Hz	Hertz; cycles per second
IC	Inspiratory capacity
IVC	Inspiratory vital capacity
K_{CO}	Transfer coefficient of the lung (*i.e.* $D_{L,CO}/V_A$)
kg	Kilograms
kPa	Kilopascals
L	Litres
L·min^{-1}	Litres per minute
L·s^{-1}	Litres per second
lb	Pounds weight
$MEF_{X\%}$	Maximal instantaneous forced expiratory flow where X% of the FVC remains to be expired
MFVL	Maximum flow–volume loop
mg	Milligrams
MIF	Maximal inspiratory flow
mL	Millilitres
mm	Millimetres
MMEF	Maximum mid-expiratory flow
ms	Milliseconds
MVV	Maximum voluntary ventilation
P_{A,O_2}	Alveolar oxygen partial pressure
PB	Barometric pressure
PEF	Peak expiratory flow
P_{H_2O}	Water vapour partial pressure
P_{I,O_2}	Inspired oxygen partial pressure
θ (theta)	Specific uptake of CO by the blood
RT	Rise time from 10% to 90% of PEF
RV	Residual volume
s	Seconds
STPD	Standard temperature (273 K, 0℃), pressure (101.3 kPa, 760 mmHg) and dry
TB	Tuberculosis
TGV (or V_{TG})	Thoracic gas volume
t_I	Time taken for inspiration
TLC	Total lung capacity
Tr	Tracer gas
t_{tot}	Total time of respiratory cycle
V_A	Alveolar volume
$V_{A,eff}$	Effective alveolar volume
VC	Vital capacity
V_c	Pulmonary capillary blood volume
V_D	Dead space volume
V_I	Inspired volume
V_S	Volume of the expired sample gas
μg	Micrograms

APPENDIX

Proposal for a standard data format for spirometry

This proposal would not preclude the use of other data formats, but would require that a spirometer should at least be able to output data in the required format. The advantage of a standard format is the ease of moving data into data repositories, such as quality control, healthcare and research databases. It should simplify and reduce the cost of data transfer when users change instrument models and manufacturers. Easier transfer of data into healthcare databases has the potential for improving the utility of lung function by making more complete data readily available to clinicians and healthcare researchers. In research and clinical settings, a standard data format should simplify and reduce the cost of transferring data into quality control software and could contribute to improved overall test quality. Finally, it is time for this change; pulmonary function is one of the last medical arenas without a standard data format.

Proposed format

The spirometry data file will consist of an American Standard Code for Information Interchange, comma-delineated file with variable length records. Comma-delineated text files are easily generated and are standard import formats for several database programs. Although some redundancies will exist, each record shall represent one curve and will be terminated with a carriage return and line feed. The ATS will distribute examples of this data format from their web site.

Table 8 shows a list of parameters that must be included in every record. If a parameter is unavailable, the space must remain blank (‘‘,,’’). The flow–time data points must be provided with a sampling interval of 0.01 s (100 samples·s^{-1}) in mL·s^{-1}. If necessary, interpolation or other techniques must

TABLE 8 List of parameters[#]

ID (patient identification)
Patient name
Data type (SP followed by E=expiratory or I=Inspiratory, followed by S=single or B=best curve)
Barometric pressure (mmHg)
Temperature (℃) used in BTPS calculation
Relative humidity (%)
FVC quality attribute (A, B, C, D or F)
FEV_1 quality attribute (A, B, C, D or F)
Effort attribute (A, B, C, D or F)
Interpretation code (see ATS interpretation scheme)
Deleted manoeuvre (Y or N)
Acceptable manoeuvre (Y or N)
Technician quality control code (A, B, C, D or F)
Computer quality code (A, B, C, D or F)
Plateau achieved (Y or N)
Review (N or R for ‘‘needs review’’ or ‘‘was reviewed’’)
Date of review (DD/MM/YYYY)
Reviewer initials
BTPS factor (x.xxx)
Spirometer manufacturer
Spirometer model
Spirometer serial number
Spirometer type
Testing facility name
City
State/region
Zip/post code
Country
E-mail
Phone number
Calibration date (DD/MM/YYYY)
Calibration time (HH:MM)
Calibration result (P or F for ‘‘passed’’ or ‘‘failed’’)
Date (DD/MM/YYYY)
Time (HH:MM)
Technician ID (technician identification code or initials)
Manoeuvre number
Age (integer years)
Height (cm)
Weight (kg)
Sex (M or F)
Race (2-character race code)
Date of birth (DD/MM/YYYY)
Reference values source (first author surname and date of publication, *e.g.* ‘‘Knudson 1983’’)
Reference values correction factor (x.xx, 1.00 for no correction)
Testing position (standing, sitting or supine)
Test type (pre-, post-, bronchodilator, methacholine concentration or dose)
FVC (mL)
Extrapolated volume (mL)
FEV_1 (mL)
FEV_6 (mL)
PEF (mL·s^{-1})
$FEF_{25–75\%}$ (mL·s^{-1})
VC (mL)
Forced expiratory time (s)
Time to PEF (ms)
Predicted FVC (mL)
Predicted FEV_1 (mL)
Predicted FEV_6 (mL)
Predicted FEV_1/FVC% (xxx.x%)
Predicted FEV_1/FEV_6% (xxx.x%)
Comments text
Original sampling interval (ms)
Blank 1 or $FEF_{25\%}$
Blank 2 or $FEF_{50\%}$
Blank 3 or $FEF_{75\%}$
Blank 4 or $FEF_{90\%}$
Blank 5
Blank 6
Blank 7
Blank 8
Blank 9
Blank 10
Number of data points
Flow data points (mL·s^{-1}; variable number contained in number of data points)
Carriage return
Line feed

[#]: All text type variables should be enclosed with double quotes (‘‘) to prevent confusion with control or data separator type characteristics.

be used to provide the 0.01-s sampling interval. The record length will vary, depending on the number of data points present in the flow–time portions of the record. The curve data must include $\geqslant$0.25 s of data points prior to the onset of the inspiratory or expiratory manoeuvre.

Volume–time curves may be calculated by adding the flow–time values ($mL \cdot s^{-1}$) and multiplying the sum by 0.01 s. To obtain the highest precision, the sum of the flow values should be calculated for each volume data point before multiplying by 0.01 s.

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