Journal of Clinical and Nursing Research, 2022, Volume 6, Issue 3
http://ojs.bbwpublisher.com/index.php/JCNR
ISSN Online: 2208-3693
ISSN Print: 2208-3685

Overview of Spirometry and the Use of Its Parameters for Asthma Monitoring in Children

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Abstract: Asthma is the most common chronic pulmonary disease in the world, affecting more than three hundred million people from different races and age groups. Childhood asthma is considered one of the main causes of increased healthcare expenditures, particularly in developing countries. Spirometry is the most essential and commonly used lung function test. It is used mainly for the evaluation of lung function to obtain reliable data used for the detection of lung diseases, such as asthma, as well as for monitoring lung health. The two spirometry parameters, peak expiratory flow rate (PEFR) and forced expiratory volume in one second (FEV1), are effective in the diagnosis and management of patients with asthma. However, FEV1 is preferred as it is a more accurate parameter compared to PEFR for the evaluation and recognition of bronchoconstriction. In children with asthma, the most commonly used lung function parameter for asthma monitoring is FEV1. It was discovered that a decrease in FEV1 is associated with an increase in asthma severity.

Keywords: Spirometry; Asthma; Children

Online publication: May 12, 2022

(This article belongs to Special Issue: All about Pharmaceutical Drug Interventions, From Inventing the Drug to its Therapeutic Effect on Patient Health)

1. Introduction

Asthma is a prevalent long-term disease of the lungs, marked by airway inflammation, airway hyperresponsiveness, and reversible airway obstruction [1]. Childhood asthma is the most common respiratory condition in children, and it is the primary cause of visits to emergency rooms, hospital admissions, and students' absenteeism, thus rendering parents absent during workdays [2,3]. This increases the burden on healthcare systems, especially in developing countries [4,5]. Its symptoms include wheezing, shortness of breath, chest tightness, and cough [5]. Asthma can be classified based on its severity: mild, moderate, and severe asthma [6].

Spirometry is a process of measuring air volume and air flow during inhalation and exhalation [7]. As children become older, they go through a dynamic developmental growth period, which includes changes in the volumes and sizes of their respiratory tracts and lungs [8]. The spirometry test is important for the diagnosis, management, and monitoring of patients who suffer from various pulmonary diseases [9]. Its measurement parameters are affected by and depend on height, weight, age, gender, race, environmental factors, patient compliance and capacity, as well as the use of effective techniques [10,11].

Pediatric spirometry is generally limited to primary healthcare clinics, despite the fact that it is simple and easy to perform at this age [12,13]. According to a previous surveillance study, barely half of the primary healthcare practitioners used spirometry testing for asthmatic children, and almost half of them did not elucidate the results in the correct manner [14]. Previously, physicians found it difficult to conduct spirometry testing for children aged two to six years old; however, nowadays better spirometry instruments (user-friendly spirometers) have been introduced, and they are equipped with additional features that make them more acceptable and reliable, thus enabling trusted spirometry testing even in pre-school children with the aid of well-trained staff [15-18].

In addition to that, other than spirometry, many methods can also be used to measure the respiratory function in newborns, infants, and young children. These methods include the interrupter method, the forced oscillation method [19], the gas washout method, the tidal breathing method, and the rapid thorax/abdomen compression method [20]. Spirometry is thought to be safe in both children and adults when it comes to the likelihood of inducing irregular heartbeats [21]. This validates the availability and importance of spirometry in asthmatic children's follow-up [22].

Spirometers are non-invasive devices that are used to examine lung function and diagnose respiratory tract and lung diseases, such as asthma and chronic obstructive pulmonary disease. These devices can measure the respiratory flow rate and the volume inhaled and exhaled (inspiratory and expiratory lung volume). Spirometers are typically designed to be light-weighted and easily transportable, in order to be used conveniently in healthcare facilities and by patients at home.

2. Types of spirometers and specific concerns

Several types and shapes of commercial digital spirometers can be found in the market. Portable hand-held electronic spirometers can measure the peak expiratory flow (PEF), forced expiratory volume in one second (FEV1) (as shown in **Figure 1**), and also the forced vital capacity (FVC). These results can be manually measured up to the predicted FEV1 and FVC normal values.

Figure 1. Front view and side view of a portable spirometer [21]

The more advanced second-generation electronic spirometers were designed to introduce interpretive visual chart designs (mainly volume/time curves) with or without printed handouts. By entering the patient's data and carrying out the spirometry test maneuver, the latest digitally-operated spirometers have the ability to calculate the percentage of the predicted normal values of several parameters (e.g., PEF percent predicted), centered on the reference database values that are stored in advance on the digital spirometer's memory. Many of these new spirometers are equipped with integrated printers and can support the connection with computers [22] (as shown in **Figure 2**).

Figure 2. MIR SpiroLab III equipped with printer and PC software [23]

When selecting an appropriate spirometer device, it is preferable to follow the periodically updated spirometry recommendations and criteria (ATS/ERS) [24,25]. It is also known that the surrounding environment can influence the volume of air, so spirometry should be corrected for body temperature and ambient pressure saturated with water vapor (BTPS) [22]. It is important to follow the manufacturer's instructions of the device (spirometer), especially regarding equipment standardization and calibration [26], upkeeping, and infection control, such as using discardable mouthpieces (tips) or filters [24]. Many upgraded versions do not need to be calibrated on a daily basis or even after performing a definite number of respiratory maneuvers as previously done before [27].

It should be noted that the lab operator or chest physician who performs the lung function test using the spirometer needs to be well-trained in correct measurement techniques [26]. According to studies [25,28], instructors or counsellors who participated in a four-hour course on appropriate techniques for spirometry testing were found to have the ability to fulfill the ATS/ERS spirometry testing standardized requirements. This confirms the importance of regular training and educational sessions at frequent intervals for maintaining a good proficiency level of spirometry testing [29].

3. Methods and steps of spirometry

The methodology of spirometry testing is the same in both, children more than six years old and adults [22]. It is crucial for the operator who performs the test to be able to identify and determine the errors in the technique, in addition to identifying and explaining the results of the test [24].

Firstly, the selection and standardization (if needed) of suitable apparatus should be carried out; then, the steps should be illustrated clearly to the patient [30]. It is important to ask the patient some questions about the drugs that he or she may have taken, such as beta blockers and bronchodilators, in addition to the timing of his or her last meal because having a full meal just before the test may affect the efficiency while conducting the test [31]. The patient should not wear tight clothing as it may affect the test results [30]. In addition, the patient should be standing or sitting upright (preferred as ATS found that the standing up position can lead to a slight increase in spirometry values) while performing the test [32].

Before carrying out the maneuver, the spirometer tip or mouthpiece should be replaced with a new one as a form of infection control precaution. According to ATS/ERS recommendations, a nose clip should be used for all lung spirometry tests [26], or the patient should be requested to pinch his or her nose gently [24,33]. The patient should also be educated on how to inhale and exhale normally; then, the patient should be asked to take a deep breath from the mouth until his or her lungs are completely full. After that, the patient should be asked to hold his or her breath and to place the mouthpiece of the spirometer between his or her lips while firmly surrounding it [34]. The patient should be instructed not to obstruct the mouthpiece with his or her tongue and cover the vent holes on the device. The patient should then blow air out via the mouthpiece as quickly and forcefully as possible until all the air has been expelled from the lungs. Verbal motivation makes difference; hence, it is important to encourage the patient to continue blowing until all trapped air in the lungs is expelled, as this aids in achieving optimum test results [33].

4. Indications for spirometry

Spirometry is very important for many diagnostic, monitoring, and public health purposes (as shown in **Table 1**) [31]. It is usually used in pediatric patients who suffer from symptoms such as chronic persistent cough and wheezing [35], as well as for children who have family history of lung diseases, those who suffer from recurrent chest infections, or in case of abnormal diagnostic tests results seen in arterial blood gas and chest radiograph [36]. Spirometry is also useful in the identification and follow-up of the disease progression in asthma and cystic fibrosis [37-40].

Table 1. Indications for spirometry [31]

Indications	Purpose
Diagnostic	To evaluate symptoms, signs, and abnormal laboratory tests.
	To measure the effect of a disease on pulmonary functions.
	To screen individuals at risk of having pulmonary diseases.
	To assess preoperative risk.
	To assess prognosis.
	To assess health status before beginning a strenuous exercise program.
Monitoring	To assess therapeutic intervention.
	To describe the course of disease that affect lung functions.
	To monitor individuals who are exposed to injurious agents.
	To monitor for adverse reactions to drugs with known pulmonary toxicity.
Disability/impairment evaluations	To assess patients as a part of rehabilitation programs.
	To assess risks as a part of insurance evaluations.
	To assess individuals for legal reasons.
Public health	Epidemiologic surveys
	Derivation of reference equation
	Clinical research

Spirometry is often used in the estimation of respiratory functions in several diseases, including blood disorders, such as thalassemia and sickle cell disease, which require blood transfusion, various types of blood cancers, chest malformations, such as in cases of pectus excavatum [41-43]. It is also useful in checking and determining preoperative respiratory functions in flaccid neuromuscular scolioidal diseases, such as cerebral palsy (CP), Duchenne muscular dystrophy (DMD), and spinal muscular atrophy (SMA) [44]. Besides the aforementioned indications, spirometry can be used as a screening tool to diagnose pulmonary diseases in school-aged children [35]. Finally, its parameters should be measured to aid in confirming the diagnosis of airway obstruction in symptomatic patients; they are not indicated for monitoring patients who do not have any symptoms [31].

5. Contraindications for spirometry

The absolute contraindications include patients who had recently undergone abdominal, chest, or even eye surgery [45]; patients who had recent myocardial infarction, coronary infarctions, lung collapse, cerebrovascular stroke, and aortic aneurysm within a period of previous three months [9]. Other contraindications include patients who have hyperventilation or breathlessness, diseases in which exerting much effort to achieve maximum ventilation capacity can cause problems (Moyamoya disease and repetitive or recurrent spontaneous pneumothorax), those who have pulmonary infection, such as tuberculosis (TB), patients who had suffered massive hemoptysis (coughing up blood) during the previous month, and patients who have uncontrolled hypertension, their systolic blood pressure (SBP) is more than 200 mm Hg, or their diastolic blood pressure DBP is more than 140 mmHg [9,22].

The relative contraindications include patients who had previously suffered from urinary incontinence, those who have chest or abdominal pain, patients who feel pain in the mouth cavity or face when biting onto the mouthpiece, and those with dementia, brain disorders, or suffering from mental retardation [9,25,30].

6. Spirometry parameters

(1) Peak expiratory flow (PEF) or peak expiratory flow rate (PEFR)
The measurement of the highest speed of expiration by using a spirometer device (in liter per second) or a peak flow meter device (in liter per minute) [46].

(2) Forced expiratory volume in one second (FEV1)
The volume of the air that is exhaled out of the lungs within the first second of forced expiration (occurs after extreme inhalation) [47].

(3) Forced vital capacity (FVC)
The total amount of air that a person exhales as quick as possible while testing for FEV (occurs after maximum inhalation) [30].

(4) FEV1/FVC ratio or FEV1%
The percentage of FVC which is exhaled in one second [48].

(5) Forced expiratory flow over the middle one-half of FVC ($FEF_{25–75\%}$)
The average air flow from the level at which 25% of FVC has been expelled out to the level at which 75% of FVC has been expelled out [49].

(6) Maximum voluntary ventilation (MVV)
The total volume of air that an individual can breathe in and exhale within a definite period of time [50].

7. Concepts of lung volumes and lung capacities

Spirometric lung volumes and capacities (**Table 2**) can be measured by using a spirometer, whereas non-spirometric lung volumes and capacities (**Table 2**) cannot be measured by using a spirometer, because a spirometer is only able to measure the volume of air entering and exiting the lungs; it is unable to measure the definite volume of air that remains in the lungs [51].

Table 2. Definitions of spirometric and non-spirometric lung volumes and capacities

Spirometric lung volumes and capacities (can be measured using spirometers)	
Tidal volume (TV)	The measured volume of air that an individual normally inhales or exhales in each breath during rest [52]
Inspiratory reserve volume (IRV)	The additional maximum volume of air that can be inhaled over the normal tidal volume [53]
Expiratory reserve volume (ERV)	The additional volume of air that can be exhaled from the lungs after a normal expiration [54]
Vital capacity (VC)	The air volume between slow maximum inspiration and slow maximum expiration [55]
Forced vital capacity (FVC)	The total volume of air that an individual can forcefully exhale following maximum inhalation [56]; the sum of tidal volume, inspiratory reserve volume, and expiratory reserve volume [57,58]
Non-spirometric lung volumes and capacities (cannot be measured using spirometers)	
Residual volume (RV)	The remaining volume of air in the lungs after maximum expiration [59]
Functional residual capacity (FRC)	The volume of air that remains in the lungs after normal exhalation (ERV + RV) [60]
Total lung capacity (TLC)	The volume of air that is in the lungs upon the maximal inspiratory effort; the sum of IRV, TV, ERV, and RV [51,61]

8. Spirometry models

Spirometry test readings always fall in one of following three models – normal model, obstructive model, and restrictive model (**Figure 3**) – in addition to the combined model. The difference between them is reflected in the amount of air that can be exhaled by the patient and its proportion in one second (the first second) [62].

8.1. Normal model

The normal spirometry range can be measured by using a spirometer, and it depends on the patient's sex, height, age, and race. If the patient's lungs and pulmonary airways are normal and healthy, the patient will be able to blow out most of the air in the lungs in the first second. Therefore, the normal spirometry model indicates that the patient's spirometry test results are normal compared to the expected results [63,64].

8.2. Obstructive model

Obstructive model occurs when the patient suffers from a lung condition that causes the narrowing of airways, such as asthma or chronic obstructive pulmonary disease (COPD). In this case, air is expelled from the lungs more slowly than in a normal person (low FEV1), and only less than 70% of the total amount of air in the patient's lungs will be expelled out in the first second [65].

8.3. Restrictive model

In the restrictive model, the total amount of air that the patient can breathe in is reduced**,** but the speed of exhaling is maintained. In this case, both FEV1 and FVC readings will be lower than the predicted results, but the ratio between them remains the same. This model can be seen in the following cases: pulmonary fibrosis, obesity, and patients with weak respiratory muscles [66].

8.4. Combined model

The combined model occurs when a combination between obstructive and restrictive models takes place. In this case, both the total amount and the speed of the expelled air are reduced. This model can be seen in severe emphysema or cystic fibrosis; it can also occur in cases of obesity [67].

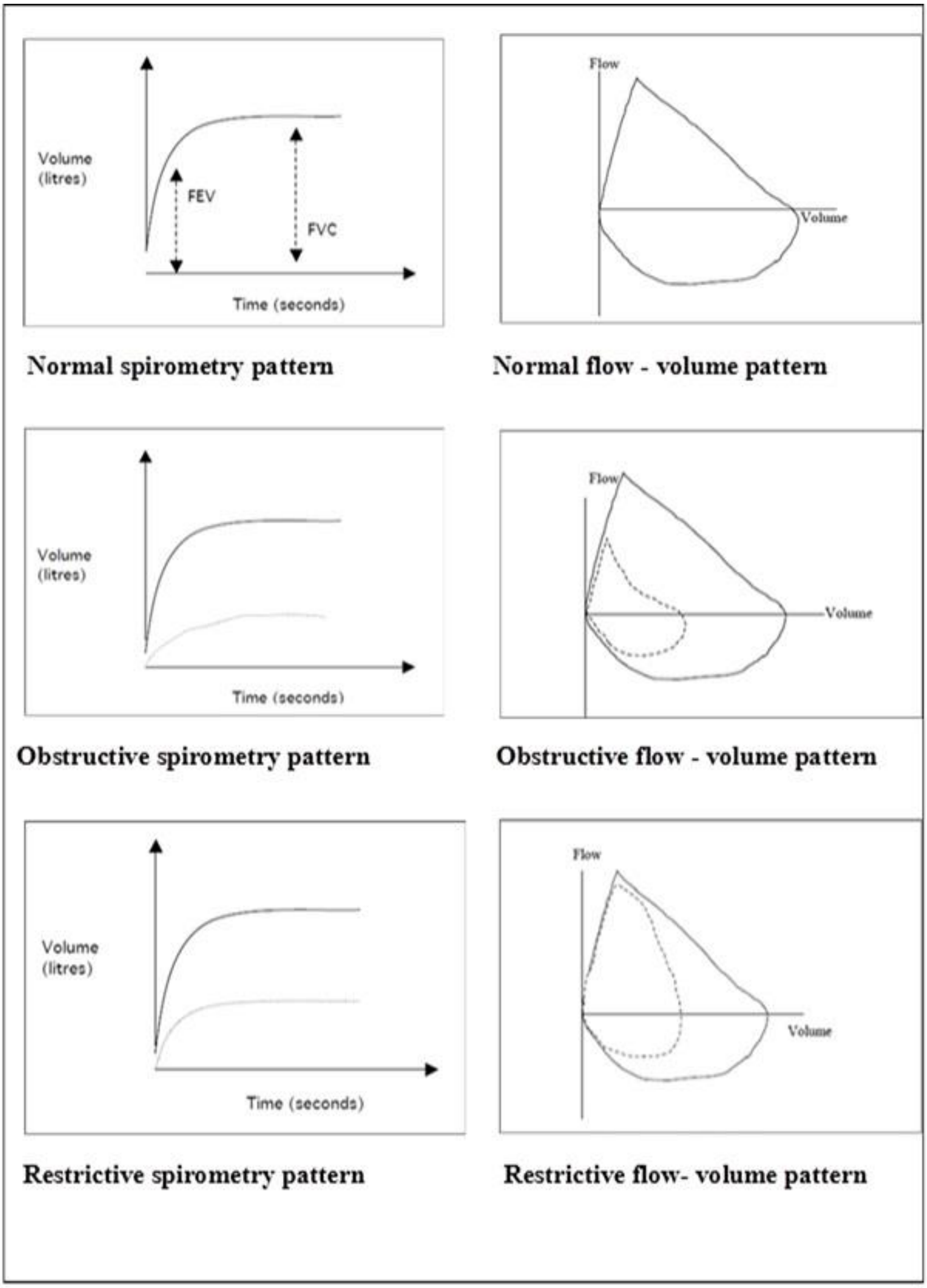

Figure 3. Different spirometry patterns [68]

9. Determining the severity of asthma in children based on spirometry readings

In pediatrics, the severity of obstruction in respiratory airways can be based on FEV1% predicted [69,70]. Spirometry parameters were shown to be associated with the severity of asthma in asthmatic patients, including pre-school children [71].

If the FEV1% predicted is 80% to 100%, this indicates mild air flow obstruction; a FEV1% predicted of 50% to 80% reveals moderate air flow obstruction; a FEV1% predicted of 30% to 50% reveals severe air flow obstruction; a FEV1% predicted of less than 30% indicates very severe air flow obstruction [22,72].

There are significant associations between FEV1% predicted and asthma symptoms, the occurrence of severe asthma attacks, the use of OCS, emergency room (ER) visits, and hospital admissions [73].

10. Role of spirometry lung functions in monitoring asthmatic children and evaluating asthma control

Compared to healthy non-asthmatic individuals, asthmatics, including children, have larger degrees of fluctuations in their pulmonary functions measured via spirometry across time [74]. Moreover, it was discovered that pulmonary functions can differ in the range of normal to extreme obstruction for the same patient. Inadequately controlled asthma is associated with a higher rate of irregularity in pulmonary functions compared to adequately controlled asthma [75]. According to the National Institute for Health and Care Excellence (NICE) guidelines, it is recommended that asthma should be monitored regularly by using spirometry at each visit or after three to six months from the initiation of therapy; a monitoring visit for follow-up is required every one to two years as a minimum [76]. It is well understood that FEV1 is considered more dependable than PEF [77]. If PEF is used, then it is recommended to use the same device for each measurement, as the measurements can differ by percentage up to 20% from one spirometer to another [63].

Upon confirming the diagnosis of a pulmonary obstructive disease, changes to FEV1 or PEF values can be used in evaluating alterations in airflow limitations (variability in the improvement or worsening of pulmonary functions and symptoms) in obstructed pulmonary airways [78].

Extreme alterations (variability) can be determined based on a period of only one day, which is known as diurnal variability, from one day to the next day, from one visit to the following visit, or periodically from one season to another season, and also from the test of reversibility (test of responsiveness) [26].

The term “reversibility” reflects rapid desired enhancements in the readings of FEV1 or PEF by measuring their values just after minutes from inhaling a dose of rapid-acting bronchodilator (such as salbutamol 200-400 mcg), or more prolonged enhancements that can occur within days or even weeks after appropriate controller medication (such as ICS) is administered [64].

10.1. Role of FEV1% predicted in asthma monitoring

Asthmatics who have lowered values of FEV1% predicted are exposed to risk of severe asthma attacks or exacerbations [79]. In addition, a low FEV1% predicted value is considered a warning indicator that reflects the liability of experiencing deteriorations in lung functions [79] despite the symptoms experienced by the patient [80]. Asthmatic children whose FEV1 is less than 60% of the predicted were found to be two times more likely exposed to the risk of severe asthma attacks in the following year compared with their counterparts whose FEV1% predicted is more than 80% [69,81]. In the presence of some symptoms, a lower FEV1% predicted will indicate that the patient’s lifestyle requires modification, or it may also indicate persistent inflammation in the respiratory airways [82,83].

Normal or near-normal values of FEV1% predicted in patients suffering from periodically repeated respiratory symptoms, especially when FEV1 is measured during the active phase, suggest the possibility of other possible causes for these symptoms, such as heart disease or cough attributable to upper airway cough syndrome (UACS), which is also known as post-nasal drip, or gastroesophageal reflux disease (GERD) [84,85].

10.2. Role of PEF in asthma monitoring

After asthma is diagnosed, PEF monitoring can be used in short term to evaluate the response to treatment, assess triggers that render symptoms worse, or to determine a baseline for designing an appropriate treatment plan [79,84,86].

A patient is likely to achieve his or her best measured PEF results from twice-daily readings after the initiation of ICS treatment of nearly two weeks [87]. Following that, the mean PEF readings continue to rise, while the diurnal variance in PEF readings falls, and this pattern continues for nearly three months [87,88].

Excessive variations in PEF readings reflect inadequate asthma control, thus predicting an elevated risk of severe asthma attacks [89]. Recently, the recommendation of long-term monitoring of PEF is only restricted to severe asthmatic patients or those with inadequate awareness about the risk of impaired airflow [83,90,91].

11. Relationship between lung function and asthma symptoms

There is no close association between lung function and asthma symptoms in case of pediatric patients [92] or adults [88]. Although numerical lung function averages can be used in conjunction with asthma symptoms in its control [93,94], the existence of a variety of symptoms is often more relevant and dependable than major changes in the patient's lung functions [95].

Studies have shown that low FEV1/FVC ratio is associated with an elevated risk of severe asthma attacks [96,96], and an FEV1 of less than 80% predicted is associated with emergency department visits, particularly in black children [98]. According to the progression and severity of the condition, it is recommended that lung functions are measured and recorded more often and periodically in asthmatic children [79]. In general, it is not necessary to ask an asthmatic patient who has been diagnosed with asthma to stop his or her regular or on demand medications before follow-up visits [99]; rather, it is preferable to maintain the same circumstances for each individual patient throughout his or her follow-up visits.

12. Conclusion

PEF and FEV1 values can be used for diagnosing, monitoring, and determining the severity of asthma in patients, particularly in children. In children, periodic monitoring of lung functions via spirometry, especially FEV1, should be considered as an important prognostic tool in the prediction of asthma exacerbations. Hence, spirometry should become more common in pediatric chest clinics for diagnosing and monitoring asthma. Chest pediatricians should be well-trained in spirometer techniques and in performing spirometry tests, as well as acquainted with approaches for interpreting spirometry results.

Disclosure statement

The authors declare no conflict of interest.

Author contributions

M.E.A.A. conceived and designed this study. All authors were involved in administrative support, provision of study materials or patients, collection and assembly of data, data analysis and interpretation, manuscript writing, as well as the final approval of this manuscript.

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