Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Clinical usefulness

Re-opening the pediatric pulmonary function laboratory during the ongoing COVID-19 pandemic

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Educational Aims

The reader will come to appreciate that:

- risk will vary with local community viral activity and individual patient.
- local testing environment must be assessed for aerosol exposure risk.
- different pulmonary function tests require different levels of protection.

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ABSTRACT

The COVID-19 pandemic continues with new waves of intensification. This review provides an update based on international recommendations concerning the conduct of pulmonary function testing in a manner to limit risk to both patient and tester.

BACKGROUND

In the November 2020 issue of Paediatric Respiratory Reviews [1], an international perspective on pediatric pulmonary function testing during the COVID-19 pandemic was published. Since that time, several national and international societies have published guidelines around testing [2–4]. The pandemic has waxed and waned and resurged around the world, reflecting local public health recommendations on mask wearing, social distancing, vaccination, travel, access to effective vaccination, and viral mutations. As such, the SARS-CoV-2 virus is becoming endemic. This article will address current recommendations during persistence of COVID-19 within our communities as we emerge from lockdowns.

During the lockdowns that many of us experienced, the marked decrease in non-SARS-CoV-2 respiratory viral infections, such as influenza and, for a while, respiratory syncytial virus (RSV) highlighted how successful mask wearing, handwashing, and social distancing could be [5,6]. We all saw a dramatic decrease in exacerbations of chronic lung conditions, such as asthma, Cystic Fibrosis and Primary Ciliary Dyskinesia [7,8], underscoring the role of respiratory viruses in pulmonary exacerbations. With loosening of restrictions, there has been a rebound in viral infections, particularly in young children not previously exposed to viruses. We are now much more cognizant of the consequences of respiratory virus exposure and that viruses can travel and be contagious through both droplet and aerosol spread [9,10].

Depending on local COVID-19 activity, pulmonary function laboratories may be closed, partially open, or fully open. A Stringency Index to assess local viral activity has been developed by the WHO [11].

PREPARING FOR PULMONARY FUNCTION TESTING

Who should undergo pulmonary function testing?

Many people, particularly children, infected with SARS-CoV-2 are asymptomatic, so that all individuals coming for testing should be considered as potentially contagious. Even more than during the pre-pandemic era, it is important to decide on whether a test is really needed. On the practical side in considering the number of tests that can be conducted on a given day, contamination precautions result in the need for more time between individuals to be tested, so fewer tests can be performed.

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Hierarchy of tests

For the purpose of assigning risk and therefore level of protection required, pulmonary function tests have often been segmented into those with a higher risk of aerosol generation and those with a lower risk. More recently, it has been recognized that regular talking can generate aerosols and that the exhortations of the tester can certainly generate aerosols, often more than generated by the test itself [12–16]. Cough is a significant aerosol-generating activity, and 50% of people will cough during or after standard pulmonary function testing [17]. Therefore, the majority of standard pulmonary function tests should be considered as at-risk procedures for exposure of the personnel. Bronchoprovocation testing, particularly with nebulized methacholine, and exercise testing require extra precautions. Personal protective equipment (PPE) requirements are discussed below.

Screening of patients

The goal of screening is risk assessment. Most laboratories question people in the 72 hours prior to them coming to the appointment and the day of their appointment. People are often not forthcoming about the presence of symptoms, so that questioning has limited reliability when negative. Some laboratories require negative COVID-19 testing prior to coming to the laboratory, or at least testing those suspected of having COVID-19. Routine testing of asymptomatic or low risk patients (e.g. vaccinated, low community viral prevalence) consumes a lot of health care resources and inconveniences the patient and family. Pulse oximetry and temperature screening may be warranted in some settings [18]. If the patient is suspected to have COVID-19, in the absence of testing, then testing should be delayed until there is resolution of symptoms and a minimum of three weeks have passed since the onset of symptoms [19,20]. Patients with chronic respiratory disease who are acutely ill can have symptoms mimicking COVID-19 and should not be tested until back to their usual status. Patients above the age of 5 years and caregivers should be masked. If possible, only the patient should be in the testing room.

Waiting room

The waiting room should be configured ideally for physical spacing. If possible, a minimum of 1- meter, and preferably 2-meter distance should be kept [21]. Hand sanitizer should be readily available. Wait times should be minimized.

Personal protective equipment (PPE)

PPE is an important component of the overall approach to preventing and controlling infection. The recommended facemask is the fit-tested N95, in Europe known as the FFP2, which filters out 95% of airborne particles. In the context where both patient and tester have been vaccinated and community prevalence is low, then a gown, gloves, face shield and surgical mask is sufficient to protect both the patient and tester [22]. A fit-tested mask (at a minimum N95, with some recommending N99) should be worn for those activities with high risk of aerosol generation (wet nebulization, bronchoprovocation challenge, exercise testing).

The testing room

Ventilation is key. The ideal setup is a negative pressure room with a high number (at least 12) of air exchanges per hour. The air exchange rate is the number of room volumes provided by the ventilation system every hour, not the number of times per hour that all the air in the room is changed. A minimum number of 6 air exchanges per hour is recommended for the standard hospital room. With such ventilation, 95% of contaminants are removed in 30 min [23]. Note that with 12 air exchanges per hour, it takes 15 min to remove 95% of the contaminants. Central ventilation systems should be configured in order to avoid returning some of the filtered air back into the room. All ventilation systems should be verified on a recurring basis. If an enhanced number of air exchanges cannot be provided, the use of high efficiency particulate air (HEPA) room filtration should be considered, whether built in, or as portable systems. Ultraviolet systems are an alternative to HEPA filtration. When there is a central system or HEPA system, windows should be sealed. When there is inadequate ventilation, opening windows will contribute to air exchange but raises the risk of contamination from the outside. Further such inconsistent aeration will cause temperature and humidity fluctuations that can interfere with the performance and accuracy of the testing equipment. Many institutions have placed plexi-glass (perspex) dividers between the patient and tester. This will prevent droplet spread, but not aerosol spread.

The equipment

Disposable bacterial/viral filters between the mouthpiece and the equipment should be employed unless they adversely affect test results and changed between patients [24]. The equipment and surfaces should be wiped down between patients according to local practice.

CONDUCTING PULMONARY FUNCTION TESTING

Spirometry pre- and post-bronchodilators

Spirometry will generate both aerosols and frequently droplets. The device needs a high efficiency in-line filter. The equipment exposed to the patient may be covered with disposable protective covers or wiped down after each patient. A plexi-glass barrier can be added to reduce droplet exposure of the tester. The room should be highly ventilated, and the tester wearing gloves, face-shield/goggles, and gown. The preferred mask is an N95, although if risk

Table 1
Pulmonary Function Test Filter and PPE Requirements.

Test	Filter	Mask	Gown + Faceshield/ Goggles
Spirometry	Yes	N95	Yes
Bronchodilator (MDI/Dry powder)	No	N95	Yes
Bronchodilator (Wet nebulized) Filter on expiratory port	Yes	N95+	Yes
Bronchoprovocation Testing Filter on expiratory port for wet nebulized *Negative pressure room recommended*	Yes	N95+	Yes
Lung volumes	Yes	N95	Yes
Carbon Monoxide Diffusion	Yes	N95	Yes
Oscillometry	Yes	N95	Yes
Multiple Breath Washout	Yes	N95	Yes
Exhaled Nitric Oxide Use in-circuit filter	Yes	N95	Yes
Nasal Nitric Oxide Use in-circuit filter	Yes	N95	No
Respiratory muscle strength Mouth	Yes	N95	Yes
Respiratory muscle strength Sniff	No	N95	Yes
Cardiopulmonary Exercise Testing	No	N95+	Yes

Legend: Derived from McGowan et al. (3). N95+: some recommend N99.

is considered low, a surgical mask can be used. The patient should remain on the mouthpiece for 2–3 tidal breaths following the manoeuvre. When the patient comes off the mouthpiece they should replace their facemask. If delivering a bronchodilator, then it is preferred to use a metered dose inhaler with a valved spacing device. A dry powder device can also be used. Note that a single deep breath hold followed by exhalation increases the amount of exhaled aerosol particles from the distal airway be a factor of 4 [25]. If wet nebulization is employed, it must be recognized that nebulization can result in environmental aerosol exposure, and SARS-CoV-2 is viable for at least 3 hours following wet nebulization [19]. For wet nebulization a N99 (FFP3) rather than an N95 (or if low risk, surgical facemask) (plus gloves, gown, and face-shield/goggles) is recommended for the tester Table 1.

Bronchoprovocation testing

Bronchoprovocation testing can provoke coughing and vigilant patient screening is recommended. Note that cough is particularly frequent in the case of using dry powder mannitol [26]. Using wet nebulization of methacholine can result in infected reservoirs in the case of wet nebulizers. Using a breath-activated nebulizer will reduce this is risk. A vibrating mesh nebulizer will avoid the reservoir coming into contact with infected particles. Even with the use of a breath-activated or vibrating mesh nebulizer, a high-quality filter should be placed on the expiratory limb. Bronchoprovocation testing is a high-risk procedure for generating aerosols. The room should have high air exchanges, or a ventilation system that does not recirculate air, a HEPA or ultraviolet cleaning capacity. For such testing it is recommended that the tester wear an N99 mask (plus gloves, gown, and face-shield/goggles). If possible, such testing should occur in a negative pressure setting, or otherwise adequate time be given for air exchanges as would be done for induced sputum collection for tuberculosis.

Lung volume measurement

If a gas washout/dilution technique is used a bacterial/viral filter needs to be in place and the patient should take 2–3 tidal breaths after a vital capacity measurement before coming off the mouthpiece. If using a whole body plethysmograph, the interior needs to be properly cleaned after each patient, with the cleaner wearing PPE. It is recommended that the tester wear an N95 mask (plus gloves, gown, and face-shield/goggles).

Diffusing capacity

An inline filter is required and the patient should take 2–3 tidal breaths after a vital capacity measurement before coming off the mouthpiece. It is recommended that the tester wear an N95 mask (plus gloves, gown, and face-shield/goggles).

Oscillometry

This test is done with the patient quietly breathing. A high efficiency inline filter is recommended.

Multiple breath washout

This test is done with the patient quietly breathing. A high efficiency inline filter is recommended.

Exhaled nitric oxide

An inline filter should be used. It is recommended that the tester wear an N95 mask (plus gloves, gown, and face-shield/goggles).

Nasal nitric oxide

An in-circuit filter is recommended. If this is not possible, then the circuit should be discarded after each test. For the tester, if a filter is not possible, physical distancing and minimizing exposure time is recommended.

Respiratory muscle strength testing

An inline filter is recommended for measurements made through a mouthpiece, but not for sniff testing. Coughing may be provoked. It is recommended that the tester wear an N95 mask (plus gloves, gown, and face-shield/goggles).

Cardiopulmonary exercise testing

Exercise testing requires the patient to breathe deeply, forcibly and frequently with significant risk of aerosol and droplet production and prolonged viral shedding. Patient screening is particularly important in this situation. Filters cause resistance particularly as accumulate water vapour and become saturated. This may impact breathing patterns and exercise performance [27] and so are not recommended. Single-use masks, sensors, turbines and gas lines are recommended. A ventilation system without recirculation is recommended. If this is not possible, then it should have a HEPA or ultraviolet cleaning capacity.

DIRECTIONS FOR FUTURE RESEARCH

- Pulmonary function testing in the office setting.
- Further clarification is needed of the risk/benefit and cost differential of portable air filtration systems [e.g. Hepafilters] vs implementing the recommended 12 or more cycles of air recirculation per hour in pulmonary function laboratories.

CONFLICTS OF INTEREST

Nil to declare.

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