AARC Clinical Practice Guideline

Infant/Toddler Pulmonary Function Tests—2008 Revision & Update

ITPFT 1.0 PROCEDURE:

Infant/toddler pulmonary function tests (ITPFTs)

ITPFT 2.0 DESCRIPTION/DEFINITION:

2.1 Infant/toddler pulmonary function tests measure a variety of pulmonary variables in subjects who are generally too young to perform, comprehend, or comply with necessary instructions for conventional pulmonary diagnostic procedures

2.2 Subjects are typically tested under conscious sedation or while sleeping and are spontaneously breathing. ITPFTs have also been performed in subjects who are mechanically ventilated.

2.3 ITPFTs may include measurements of:

2.3.1 Passive respiratory mechanics, [1-35]

2.3.2 Dynamic respiratory mechanics, [32, 33, 35-39]

2.3.3 Tidal breathing measurements, [1, 35, 40 -42]

2.3.4 Partial expiratory flow-volume curves, [2-7, 9, 12-14, 17, 35, 43-68]

2.3.5 Raised volume rapid thoracoabdominal compression technique, [12, 24, 35, 52-59, 68-89]

2.3.6 Whole-body plethysmography, [9, 32, 35, 64, 84, 85, 90-101]

2.3.7 Gas dilution techniques, [7, 10, 11, 14, 20, 26-29, 35, 43, 51, 90-92, 95, 99,100, 102-109] and

2.3.8 Forced deflation technique in intubated subjects. [110, 111]

2.4 Common indices measured using these various techniques includes:

2.4.1 Passive respiratory mechanics: total respiratory system compliance (Crs); total respiratory system resistance (Rrs); and time constant (Trs) [8, 33, 34]

2.4.2 Dynamic respiratory mechanics: lung compliance (C_L); lung resistance (R_L); respiratory rate (RR), and tidal volume [33, 38]

2.4.3 Tidal breathing measures: RR; time to reach peak tidal expiratory flow (t_{PTEF}); total expiratory time (t_E); ratio of t_{PTEF}/t_E [41, 42]

2.4.4 Partial expiratory flow-volume curves: maximal flow at functional residual capacity (VmaxFRC) [49, 68]

2.4.5 Raised volume rapid thoracoabdominal compression technique: forced vital capacity (FVC); forced expired volume at 0.5 and 0.75 seconds respectively (FEV0.5, FEV0.75); forced expiratory flow at 25%, 50%, 75% and between 25% and 75% of FVC (FEF25, FEF50, FEF75, FEF25-75) [68, 73]

2.4.6 Whole body plethysmography: plethysmographic functional residual capacity (FRCpleth); airway resistance (Raw) [97, 101]

2.4.7 Gas dilution techniques: helium dilution (FRCHe), nitrogen washout (FRCN2), breath-by-breath inert gas washout or multiple breath washout (MBW) techniques measure lung clearance index (LCI) or mixing ratios (MR) [105, 109]

2.4.8 Forced deflation: FVC, maximum expiratory flows at 25 and 10% of FVC (MEF25, MEF10) [111]

2.5 Although these procedures are intended primarily for neonates and infants, some older subjects may be successfully evaluated, if appropriately sized equipment is employed and methodology limitations are well understood.

2.6 The maneuvers used during the raised volume technique are being used to acquire motion free images during chest CT at end inspiration and end exhalation in infants and children. [112]

2.7 Investigational techniques in infants such as forced oscillation and interrupter resistance have been described. [113-117] Consensus regard-

ing methodology for these techniques is not available for infants; therefore, the techniques are briefly described in section 8 of this document.

2.8 Hardware Considerations:

2.8.1 Size appropriate measurement devices, such as pneumotachometers with appropriate flow range are critical. [118]

2.8.2 When setting up equipment, one should use tubing sizes and connections that create the minimum possible mechanical deadspace. It is important to remember that modifying connections near pneumotachometers or flowmeters may adversely affect measurement accuracy. [118]

ITPFT 3.0 SETTING:

3.1. Testing may be performed, in a variety of settings including, but not limited to: hospital laboratories, intensive and intermediate care units, and specialized clinics. It is critical to note that the infants are often undergoing conscious sedation and must be appropriately monitored in the specific setting. When performing these tests, the top priority is the safety of the infant and toddler. [118, 119] Please see sections 10 and 11 for details regarding monitoring and personnel.

ITPFT 4.0 INDICATIONS:

Indications for ITPFTs include the following:

4.1 To serve as an outcome measure in epidemiologic research [1, 2, 3, 12, 17, 32, 47, 48, 50, 58, 63, 71, 75, 76, 79, 93, 120]

4.2 To improve one's understanding of the natural history of lung growth, or diseases presenting in infancy (e.g., cystic fibrosis, bronchopulmonary dysplasia, wheezing illnesses) [4, 9, 10, 11, 13, 14, 15, 20, 21, 23, 25, 26, 31, 36, 40, 43, 44, 46, 51, 55, 56, 59, 65, 69, 70, 74, 77, 83, 88, 89, 90, 92, 94, 99, 102, 108, 120]

4.3 To evaluate therapeutic responses (e.g., to medication or respiratory interventions) [5, 6, 7, 27, 28, 29, 30, 52, 61, 86,120]

4.4 To help in predicting the risk of subsequent pulmonary dysfunction based upon initial testing. [63, 67, 70, 120]

4.5 To provide physiologic measures of lung function in a variety of diseases [4, 9, 10, 11, 13, 14, 15, 20, 25, 31, 36, 40, 43, 46, 50, 51, 52, 55, 65, 69, 70, 78, 85, 88, 89, 90, 91, 92, 94, 108, 120]

ITPFT 5.0 CONTRAINDICATIONS:

It is absolutely critical that prior to initiating ITPFTs the technologist and physician carefully evaluates the patient. Clinical judgment and/or caution should be exercised due to the need for sedation and invasiveness of some of these techniques.

5.1. Absolute Contraindications (based on the recommendations of the writing committee):

5.1.1 Active pulmonary bleeding,

5.1.2 Open chest wound,

5.1.3 Untreated or tension pneumothorax,

5.1.4 Past history of intolerance to sedation,

5.1.5 Significant upper airway obstruction,

5.1.6 Seizure disorder (if performing the raised volume technique; the multiple inflations may lead to a drop in carbon dioxide levels, thus a drop in seizure threshold),

5.1.7 Hemodynamically significant congenital heart disease,

5.1.8 If patient has not remained without food and/or drink based on the conscious sedation policy of the individual institution,

5.1.9 Naso-facial deformities that prevent effective mask seal or increase risk of gastric insufflation.

5.2 Relative Contraindications (based on the recommendations of the writing committee):

5.2.1 Medical conditions that could compromise patient's condition if ventilatory support is temporarily interrupted when performing ITPFTs,

5.2.2 Central hypoventilation,

5.2.3 Pre-existing central nervous system depression or neurologic impairment such as hydrocephalus,

5.2.4. Severe gastroesophageal reflux, esophagitis or gastritis,

5.2.5 Uncooperative or combative patient,

5.2.6 Patients with pacemakers (Thoracoabdominal compression technique (Hugs) may lead to possible dislodging of wires),

5.2.7 Febrile patients, or a recent history URI, pneumonia or excessive coughing.

ITPFT 6.0 PRECAUTIONS/HAZARDS AND/OR COMPLICATIONS:

Due to the need for sedation and the potential invasiveness of the procedure, the technician performing

the technique should be an expert in airway management and monitoring of infants and toddlers. Although ITPFTs are generally safe procedures, the following untoward events may occur: [121-123]

6.1 Vomiting with aspiration with consequent apnea and laryngospasm and/or bronchospasm (The forced deflation technique requires tracheal intubation), [111]

6.2 Pneumothorax,

6.3 Loss of airway patency leading to increased upper airway obstruction (due to sedation), [121-123]

6.4 Transmission of contagion via improperly cleaned equipment or as a consequence of the inadvertent spread of droplet nuclei or body fluids (patient-to-patient or patient-to-technologist) Infection control is critical (see section 13), [124-126]

6.5 Oxygen desaturation due to (a) worsening of ventilation-to-perfusion mismatch and hypoventilation as a consequence of sedation and/or positioning; [121-123] (b) interruption of oxygen therapy or failure to preoxygenate the patient prior to performing the forced deflation technique; (c) temporary loss of distending pressure;

6.6 Bradycardia secondary to the sedation, [122,123]

6.7 Cough,

6.8 Hypocapnia or dizziness (during the raised volume technique), [121]

6.9 Paradoxical excitement from the chloral hydrate (common sedative used), [121]

6.10 Gastrointestinal side effects such as nausea, vomiting, diarrhea from chloral hydrate, [121-123]

6.11 Gastric distention or aerophagia from air entering the esophagus. [73]

ITPFT 7.0 LIMITATIONS OF METHODOLOGY/ VALIDATION OF RESULTS:

ITPFTs have classically been performed at large medical centers with dedicated pediatric staff. Limitations of performing these tests are: (1) the need for at least two trained personnel to perform the maneuvers; (2) the sedation requirements, (3) inadequate sleep deprivation of the patient, and (4) the complexity of both performing and interpreting the data. The ATS/ERS Working Group of Infant Lung Function Testing has published guidelines to standardized performance and interpretation of ITPFT results.

7.1 Methodology and limitations for ITPFT techniques are:

7.1.1 Raised volume rapid thoracoabdominal compression technique (RVRTC).

7.1.1.1 RVRTC Methodology: [35, 68, 73]

7.1.1.1.1 Inflatable jacket is wrapped around the thorax of the sedated, supine infant. There should be a minimum of 3 finger breadths between the infant and the jacket to prevent restriction of lung volumes. If the jacket is too tight, there is a restriction of lung volumes. If the jacket is too loose, there is a delay in the initiation of the "hug." [73]

7.1.1.1.2 A clear facemask secured to the face with therapeutic putty is attached to a circuit containing a pneumotachograph, and placed around the infant's nose and mouth. [35, 68, 73]

7.1.1.1.3 The infant's lung volume is increased to an airway pressure of 30 cm H_2O (V30) using a pop-off in the circuit attached to the facemask. [35, 68, 73]

7.1.1.1.4 Cricoid pressure could be applied during the inflation maneuver to limit gas entry into the stomach. [79, 82, 84]

7.1.1.1.5 After the inflation to V30, the infant is allowed to passively exhale. These inflation-passive exhalation maneuvers are repeated until the infant exhibits a short respiratory pause. [35, 68, 73]

7.1.1.1.6 At the end of the V30 inflation, the jacket is inflated to a preset pressure to initiate the forced exhalation maneuver. [35, 68, 73]

7.1.1.1.7 The above maneuver is repeated at increasing jacket pressures until flow limitation is

achieved. (i.e. no further increases in flow despite an increase in jacket pressure of 10 to 15 cm H_2O) [35, 68, 73]

7.1.1.2 RVRTC Limitations: [68, 73]

7.1.1.2.1 Increased upper airway resistance may interfere with the accuracy of intrathoracically determined flows.

7.1.1.2.2 Airflow may be affected by upper airway obstruction and nasal compression or by head and neck positioning. (Subject positioning must minimize pharyngeal narrowing.) [73]

7.1.1.2.3 Reflex glottic closure (complete or partial) may limit flow. [73]

7.1.1.2.4 Hug pressures may range from ≤ 40 to > 100 cm H_2O. However, if too little pressure is transmitted to the pleural space, flow limitation will not be achieved.[127] Conversely, excessive pressures may alter the shape of the curve, via negative effort dependence. [73, 81]

7.1.1.2.5 Improperly sized and/or positioned "hug" bag may lead to inaccurate results [73]

7.1.1.2.6 Pneumotachometer with inappropriate flow range may lead to inaccurate results [73]

7.1.1.2.7 Sedation may affect airway patency, thus data results [68]

7.1.1.2.8. Air may enter the stomach leading to gastric distension and possibly a decrease in lung volumes [68, 73, 128]

7.1.1.2.9 Inability to achieve an adequate seal with the facemask. [68, 73]

7.1.2 Partial Flow-Volume Curves:

7.1.2.1 Methodology of Partial Flow-Volume Curves [35, 49, 68]

7.1.2.1.1 Sedated infant is placed supine; facemask is placed around nose and mouth and secured with therapeutic putty; inflatable jacket wrapped around thorax

7.1.2.1.2 Facemask is attached to a pneumotachometer

7.1.2.1.3 Infant allowed to tidal breathe through the circuit until stable tidal breathing established.

7.1.2.1.4 Once stable tidal breathing established, jacket inflated to initiate forced exhalation.

7.1.2.1.5 Maneuver repeated at increasing jacket pressures until flow limitation (no increase in flows despite an increase in jacket pressure of 10 to 15 cm H_2O) presumably has been achieved.

7.1.2.1.6 Flow measured and referenced to functional residual capacity (FRC)

7.1.2.2 Limitations of Partial Flow-Volume Curves [35, 49, 68]

7.1.2.2.1 Increased upper airway resistance may interfere with the accuracy of intrathoracically determined flows.

7.1.2.2.2 Airflow may be affected by upper airway obstruction and nasal compression or by head and neck positioning. (Subject positioning must minimize pharyngeal narrowing.)

7.1.2.2.3 Flows are referenced to FRC, which is a dynamic lung volume affected by sleep state and sedation. [68]

7.1.2.2.4 Reflex glottic closure (complete or partial) may limit flow.

7.1.2.2.5 Variations in end-expiratory levels, or FRC, may affect measurements 'at FRC' making therapeutic evaluations (e.g., efficacy of bronchodilator) difficult. [68]

7.1.2.2.6 Flow limitation may not be reached [35, 68]

7.1.2.2.7 The flow-volume relationship produced by the partial flow-volume curve technique represents a small portion of the entire maximal expiratory flow-volume curve [35, 68]

7.1.2.2.8 Improperly sized and positioned "hug" bag may lead to false results.

7.1.2.2.9 Pneumotachometer with inappropriate flow range may lead to inaccurate results.

7.1.2.2.10 Infant does not exhale to residual volume [35]

7.1.2.2.11 Inability to achieve an adequate seal with the facemask. [49]

7.1.3 FRC measured via Plethysmography (FRCpleth)

7.1.3.1 FRCpleth Methodology [35, 97, 101]

7.1.3.1.1 Sedated infant placed in plethysmograph, facemask placed around infant's nose and mouth and secured with therapeutic putty and box closed.

7.1.3.1.2 Respiratory frequency of infant observed until thermal equilibrium reached.

7.1.3.1.3 Once equilibrium is achieved, infant's airway occluded at end-inspiration for 2 to 4 respiratory efforts using a valve in the circuit.

7.1.3.1.4 The lack of a decay in the mouth pressure during the occlusion confirms the absence of a leak.

7.1.3.1.5 The maneuver is repeated at least 3 to 5 times until a minimum of 3 acceptable FRC measures are obtained

7.1.3.1.6 Tidal volume is subtracted from FRCpleth to obtain the true FRC at end-expiration

7.1.3.1.7 Fractional lung volumes are not possible using the RVRTC technique and FRCpleth measures. [84, 90] However the expiratory reserve volume (ERV) is measured following the RVRTC maneuver after the infant returns to stable end expiratory level (FRC). The ERV is defined and measured as the lung volume difference between the end of FVC and the stable end-expiratory level (FRC). RV is obtained by subtracting ERV from FRC. Forced vital capacity (FVC) measured during the RVRTC maneuver is added to the RV to obtain total lung capacity (TLC). [84, 90]

7.1.3.2 FRCpleth Limitations

7.1.3.2.1 Occlusion usually occurs at end-inspiration because the infant tolerates this maneuver better than occluding at end-expiration; there is less glottic closure; and less signal to noise ratio. Investigators have also hypothesized that FRC obtained at end-expiration may be inaccurate due to more airway closure at these lower lung volumes. [35, 101, 129-132]

7.1.3.2.2 One must assume that during the occlusion, when there is zero flow that the upper airway pressure equilibrates with the alveoli pressure. Lack of equilibration could lead to inaccurate results. [101]

7.1.3.2.3 FRC is a variable lung volume and changes with sleep state and sedation [35]

7.1.3.2.4 FRCpleth has been reported to be inaccurate in wheezy infants after bronchiolitis [129, 133]

7.1.3.2.5 Minimal published data is available for fractional lung volumes. [84, 90]

7.1.4 Gas Dilution and Ventilation Inhomogeneity Techniques

7.1.4.1 Gas Dilution Methodology

7.1.4.1.1. All gases used in the dilution techniques are inert, thus are not part of gas exchange and are minimally soluble in blood [109]

7.1.4.1.2 Open-circuit Nitrogen Washout Methodology [35, 105,109]

7.1.4.1.2.1 Tidal breathing observed in sedated infant to ensure stable FRC

7.1.4.1.2.2 At FRC, subject switched to a circuit and begins to breathe 100% oxygen

7.1.4.1.2.3 Bias flow is continuous and is above the inspiratory flow rate of the infant.

7.1.4.1.2.4 Expired nitrogen from the mixing chamber is continuously analyzed

7.1.4.1.2.5 Maneuver continues until nitrogen levels drop to a baseline level

7.1.4.1.2.6 FRC is equal to the volume of nitrogen expired divided by the initial volume of nitrogen in the lungs minus 0.02 (the factor, 0.02, represents the nitrogen concentration where washout is terminated).

7.1.4.1.3 Closed-Circuit Helium Methodology [35, 109]

7.1.4.1.3.1 Infant's tidal breathing observed until FRC stable.

7.1.4.1.3.2 Once FRC is stable, the infant is connected to a circuit with the known volume of helium gas (V1) at FRC.

7.1.4.1.3.3 Rapid helium analyzer must be used

7.1.4.1.3.4 Infant tidal breathes until equilibration occurs between the infant's lungs and chamber containing the helium

7.1.4.1.3.5 Once equilibration has occurred, V2 is calculated with the following equation: V1 X C1 (initial concentration of helium) = (V1 + V2) • C2 (concentration of helium at the end of gas mixing). V2 is FRC.

7.1.4.1.4 Breath-by-Breath Washout Methodology [109, 134]

7.1.4.1.4.1 To perform this method, the infant breathes in an inert gas, which may be nitrogen, helium or SF_6 (sulfur hexaflourane).

7.1.4.1.4.2 This method consists of a wash-in and washout phase unless using 100% oxygen during nitrogen washout.

7.1.4.1.4.3 During the wash-in phase, the infant breathes the gas mixture containing the inert gas through the mask until equilibration is achieved.

7.1.4.1.4.4 During the washout phase, the gas supply is disconnected.

7.1.4.1.4.5 The infant breathes room air until the tracer gas concentration reaches a certain threshold (below 0.1%)

7.1.4.1.4.6 Since nitrogen is excreted from other tissues, the washout for this gas continues until the gas concentration is 2%.

7.1.4.1.4.7 Different gas analyzers may be used for this technique including mass spectrometry, infrared technology and the ultrasonic device.

7.1.4.1.4.8 FRC is equal to the total exhaled tracer gas volume divided by the difference between the gas concentration at the beginning and end of the washout.

7.1.4.1.4.9 Measures of ventilation of inhomogeneity can be measured such as lung clearance index (number of lung volume turnovers required to complete the washout OR the ratio of cumulative expired volume needed to complete the washout divided by FRC), mixing ratio (ratio of actual number of breaths compared to ideal number of breaths that lowers the tracer gas to 1/40 of the starting concentration).

7.1.4.2 Gas Dilution Limitations

7.1.4.2.1 Leaks invalidate measurements [105]

7.1.4.2.2 The time required to wait between sequential FRC measures may be inaccurate [105]

7.1.4.2.3 Open-circuit Nitrogen Washout Limitations [35, 105, 109]

7.1.4.2.3.1 Errors may occur when switching to FRC

7.1.4.2.3.2 Washout may be longer in infants with lung disease

7.1.4.2.3.3 FRC measures only communicating airways, not the non-communicating airways; therefore, FRC measure may be inaccurate in severe obstructive airways disease.

7.1.4.2.3.4 Nitrogen analyzers may be inaccurate due to non-linearity

7.1.4.2.4 Closed-Circuit Helium Limitations [35]

7.1.4.2.4.1 Equilibration may take up to 5 minutes in infants with lung disease

7.1.4.2.4.2 Operator expertise is essential for accurate measures.

7.1.4.2.5 Breath by Breath Washout Limitations [109, 134]

7.1.4.2.5.1 Gas concentrations must be measured accurately during rapid tidal breathing

7.1.4.2.5.2 Gas concentration must be correlated with the correct flow sample

7.1.4.2.5.3 Pneumotachometer must be calibrated correctly with the various gases that can be used.

7.1.4.2.5.4 Deadspace must be minimized.

7.1.4.2.5.5 If using 100% oxygen, this may alter the infant's respiratory rate

7.1.4.2.5.6 Mass spectrometry is expensive

7.1.4.2.5.7 No standards for performing the technique in infants are available.

7.1.5 Compliance and Resistance Measurements

7.1.5.1 May be measured through passive or dynamic techniques

7.1.5.2 Dynamic Measures [33, 35]

7.1.5.2.1 Dynamic measures are evaluated during spontaneous breathing with ongoing respiratory muscle activity

7.1.5.2.2 Dynamic measures may occur through (1) the analysis of airway resistance using plethysmography, (2) the evaluation of lung resistance and compliance using esophageal manometry and (3) forced oscillation techniques.

7.1.5.2.3 Airway resistance measured during plethysmography (Raw) [35, 97, 101]

7.1.5.2.3.1 Infant is placed in a plexiglass plethysmograph

7.1.5.2.3.2 Unlike the adult, the infant is unable to pant, thus the circuit contains a heated, humidified gas at BTPS that the subject rebreathes.

7.1.5.2.3.3 Airway resistance is calculated from the flow measured at the pneumotachograph and from the difference in pressure between the alveoli and the opening of the subject's airway. (Raw = DP/ flow)

7.1.5.2.3.4 Since the heated system is cumbersome, recently electronic compensation has been attempted.

7.1.5.2.3.5 Other measures are possible, using FRC measured during plethysmography, including airway conductance (reciprocal of Raw), specific resistance (Raw X FRC) and specific airway conductance (airway conductance divided by FRC)

7.1.5.2.4 Dynamic Respiratory Mechanics using esophageal manometry [33, 35]

7.1.5.2.4.1 Esophageal catheter must be placed when infant is awake or sedated.

7.1.5.2.4.2 Correct placement is critical for accurate

transpulmonary pressure measurements. Esophageal pressure reflects pleural space changes due to close apposition of esophagus to pleura.

7.1.5.2.4.3 May use liquid-filled catheter, esophageal balloon or catheter tip pressure transducer to perform measurements.

7.1.5.2.4.4 During these measures, tidal volume, flow and pressures changes at the airway opening and esophagus are measured with the aid of a pneumotachometer or flow meter.

7.1.5.2.4.5 Stable tidal breathing is essential.

7.1.5.2.4.6 Compliance and resistance are assessed using measures of volume, flow and transpulmonary pressures. Methods of analysis include the Mead-Whittenberger technique, the least-squares regression technique, the multiple linear regression technique and the Mortola-Saetta technique.

7.1.5.3 Passive Respiratory Mechanics [8, 33]

7.1.5.3.1 May use a single or multiple occlusion technique

7.1.5.3.2 For occlusion techniques, the Hering-Breuer reflex must be invoked to elicit relaxation of the respiratory system.

7.1.5.3.3 For the both occlusion techniques, a facemask is placed around the infant's nose and mouth.

7.1.5.3.4 During the single occlusion technique, at least 5 tidal breath are collected and a brief occlusion takes place at end inspiration

7.1.5.3.5 During the single occlusion technique, compliance is measured as the change in volume divided by the change in pressure (calculated as the difference between atmospheric pressure and plateau achieved during the occlusion).

7.1.5.3.6 Other parameters that may be measured include: resistance of the respiratory system and time constants.

7.1.5.3.7 During the multiple occlusion technique, the airway opening is briefly occluded at different volumes above the end expiratory level

7.1.5.3.8 During the multiple occlusion technique, the measured airway opening pressure and volume are recorded on x-y plots and the slope is analyzed as the compliance of the respiratory system.

7.1.5.3.9 Modifications of the occlusion techniques include a weighted spirometry technique (very little published since the early 1990s), expiratory volume clamping and assessing compliance using the RVRTC technique from near total lung capacity. [21, 25]

7.1.5.4 Limitations of Dynamic Measures

7.1.5.4.1 Limitations of Raw measures [97, 101]

7.1.5.4.1.1 Complex equipment is needed to measure Raw.

7.1.5.4.1.2 Traditionally, a heated rebreathing bag is needed for Raw measurements

7.1.5.4.1.3 Electronic compensation has been introduced in place of the heated rebreathing bag for Raw measurements, but validation is needed.

7.1.5.4.2 Limitations of Dynamic measures obtained with an esophageal catheter [33]

7.1.5.4.2.1 Improper placement of esophageal catheters may lead to erroneous results of resistance and compliance measures.

7.1.5.4.2.2 Esophageal pressures not accurately measured with chest wall deformities or severe airway obstruction.

7.1.5.4.2.3 Resistance measures dominated by upper airway resistance

7.1.5.4.2.4 No commercially available device

7.1.5.4.2.5 Dynamic respiratory mechanic measures have not been standardized.

7.1.5.4.3 Limitations of Passive respiratory mechanics [33]

7.1.5.4.3.1 Assumption of pressure equilibration between airway opening and alveoli not valid in severely obstructed patients.

7.1.5.4.3.2 Measures total respiratory system resistance and compliance; unlike dynamic measurements where respiratory system components may be partitioned due to the esophageal pressure measures

7.1.5.4.3.3 Resistance measures dominated by upper airway resistance, thus changes in lower airway resistance may not be accurately measured

7.1.6 Tidal Breathing Maneuvers

7.1.6.1 Tidal Breathing Methodology [41, 42]

7.1.6.1.1 Two ways to obtain tidal breathing measures: (1) Placing a facemask around infant's nose and mouth and measuring flow and volume using a pneumotachometer and (2) respiratory inductive plethysmography, using bands that measure chest and abdominal wall movement

7.1.6.1.2 Simple, noninvasive technique

7.1.6.1.3 Respiratory rate, tidal volume (Vt), and the ratio of time to peak tidal expiratory flow and total expiratory time (t_{PTEF}/ t_E) are common parameters measured.

7.1.6.1.4 Phase angle is measured using inductive plethysmography and reflects the synchrony or asynchrony of the abdominal wall compared to the rib cage

7.1.6.2 Tidal Breathing Limitations [35, 41, 42]

7.1.6.2.1 Minimal deadspace is critical

7.1.6.2.2 There may be variability of the respiratory rate and volume, which may be due to sleep state, weight or gestational age

7.1.6.2.3 Tidal breathing may provide additional objective information when combined with other clinical tools.

7.1.7 Forced Deflation

7.1.7.1 Forced Deflation Methodology [111]

7.1.7.1.1 The infant's lungs are inflated to 40 cm H_2O pressure for at least 3 seconds then deflated with the use of negative pressure (-40 cm H_2O)

7.1.7.1.2 Lungs deflated until infant reaches RV or for a maximum of 3 seconds.

7.1.7.1.3 This technique requires intubation and heavy sedation.

7.1.7.1.4 Flow limitation is possible

7.1.7.2 Forced Deflation Limitations [111]

7.1.7.2.1 A cuffed endotracheal tube is desirable to prevent leaks

7.1.7.2.2 Endotracheal tube size may affect flows

7.1.7.2.3 Deep sedation and/or paralysis is required

7.1.7.2.4 Deflation may affect testing due to an effect on bronchoconstriction; however, recruitment with the inflation maneuver may offset this potential problem.

7.2 Reference values are critical when performing ITPFTs; however, there is a lack of these values due to the difficulty of recruiting controls and due to ethical reasons associated with sedation of healthy infants. Published reference data is lacking. Lack of appropriate reference data leads to difficulty in assessing disease versus normal growth/development. 60, [79, 84, 96, 120]

ITPFT 8.0 RECENT TECHNIQUES

8.1 Forced Oscillation: [115-117, 120, 135]

8.1.1 May be ideal in infants since requires no cooperation and can be performed without sedation.

8.1.2 Respiratory impedance assessed by applying oscillations (usually from a loudspeaker) to the airway opening.

Impedance is equal to the ratio of pressure and flow measured at the airway opening during the application of these oscillations. Impedance represents the real (resistive) and imaginary (reactance) components of the respiratory system. [116, 135]

8.1.3 Measurements may be assessed at a low-frequency, which leads to partitioning of airway and tissue mechanics. For this technique, a brief respiratory pause is necessary and is achieved using inflation pressures at the airway opening to induce the Hering-Breuer reflex. [117]

8.1.4 Measurements have also been assessed at high-frequency, with results reflecting airway wall mechanics [115]

8.2 Interrupter Resistance [113, 114, 135]

8.2.1 May be ideal in infants since requires no cooperation and can be performed without sedation. [114]

8.2.2 Measured by applying a brief interruption to airway flow during tidal breathing.

8.2.3 Pressure and flow measured at the airway opening during these brief interruptions. Resistance calculated as the ratio of the pressure change versus flow measured at the airway opening during the brief interruption.

ITPFT 9.0 ASSESSMENT OF NEED:

Although progress has been made in the clinical use of ITPFTs, this tool has historically been used in the research setting.

ITPFT 10.0 ASSESSMENT OF OUTCOME/TEST QUALITY:

Outcome and test quality are determined by ascertaining that the desired information has been generated for the specific indication(s) and that the information is valid and reproducible. Each laboratory should standardize procedures and demonstrate inter-technician reliability. Test results can only be considered valid if they are derived according to and conform to established laboratory quality control and quality assurance protocols. These protocols should address test standardization and reproducibility criteria that include the methodology used to derive and report the ITPFTs. [136]

10.1 ITPFTs performed for the listed indications are valid only if the instrumentation functions acceptably and the maneuvers are obtained in an acceptable, reproducible fashion.

10.2 Report of test results should contain a statement by the technician performing the test about test quality and if appropriate, which recommendations were not met.

ITPFT 11.0 RESOURCES:

11.1 Equipment: Equipment specifications should conform to recognized standards [8, 49, 73, 97, 105, 118] and where applicable, be FDA approved.

11.1.1 Distinctive pneumotachograph, helium analyzer and nitrogen analyzer perfor-

mance specifications. Appropriate use of gas analyzers is dependent upon the methodology employed. [118]

11.1.2 Gases must be medically certified.

11.1.3 Size-appropriate resuscitation equipment (including appropriate pharmacologic agents) must be readily available. [118, 119]

11.1.4 Sedation monitoring equipment must be available (e.g., continuous pulse oximetry with pulse rate and capnograph). [118, 119]

11.1.5 Calibrated stadiometer and scale for accurate height and weight measurements (respectively) on the day of the procedure

11.2 Personnel: [118]

11.2.1 ITPFTs should be performed under the direction of a physician trained in infant pulmonary function testing methodologies (including limitations and applications). The value of ITPFT results are compromised when a test is administered and/or interpreted by inadequately trained personnel.

11.2.2 Testing personnel should be specifically trained (with verifiable training and demonstrated competency) in all aspects of ITPFTs, including equipment theory of operation, quality control, and test outcomes relative to diagnosis and/or medical history. Proficiency must also be demonstrated relative to technician's ability to calibrate equipment, apply ancillary devices to the patient, perform the test, monitor the patient and determine the quality of the test.

11.2.2.1 Testing personnel should, at minimum, be trained in basic life support and preferable to have advance (neonatal [NRP] or pediatric [PALS]) life support training

11.2.2.2 At least one of the following credentials is recommended: CRT, RRT, CPFT, RPFT, LPN, RN, NP, CRNA, PA-C, MD, DO.

ITPFT 12.0 MONITORING: (Also see Section 10.0 ASSESSMENT OF TEST QUALITY)

The following should be monitored during ITPFT determinations: [136]

12.1 Test data of repeated efforts (i.e., reproducibility of results) to ascertain the validity of the results (The final report should contain a statement about testing conditions and test quality.)

12.2 The final report should contain the requested parameters and lung-volume corrected values (if applicable).

12.3 The patient for any adverse effects of testing [118]

12.3.1 Infants undergoing conscious sedation should be pre-assessed prior to sedation, be appropriately monitored during and after IPFT, with sedative information included in the final report. [118, 119]

12.3.2 Patients on supplemental oxygen may require periods of time to rest (on oxygen) between trials.

ITPFT 13.0 FREQUENCY:

The frequency at which ITPFT measurements are repeated depends on the clinical status of the patient and the indications for performing the test.

ITPFT 14.0 INFECTION CONTROL:

Infant/toddler pulmonary function tests are relatively safe procedures, but the possibility of cross-contamination exists, either from the patient-patient or patient-technologist interface. [124-126]

14.1 Universal Precautions (as published by the Centers for Disease Control) should be applied in all instances in which there is evidence of contamination with blood (e.g., pneumotachometers and adapters). Although Universal Precautions do not apply to saliva or mucus unless it contains blood, other potentially hazardous organisms may be present in these fluids even in the absence of blood, and the appropriate use of barriers and hand washing are recommended.

14.2 Due to the nature of some ITPFT maneuvers and the possibility of coughing when the test is performed by subjects with active infection with *M tuberculosis* or other airborne organisms, the following precautions are recommended: [124]

14.2.1 If a maneuver is likely to stimulate or induce a cough, disposable gloves, protective outerwear, along with masks (which comply with OSHA requirements) and protective eyewear should be utilized. This

personal protective equipment is also to be used when testing patients with known or suspected, potentially infectious airborne disease(s).

14.2.2 The room in which ITPFTs are performed should meet or exceed the recommendations of U.S. Public Health Service for air changes and ventilation. The most desirable arrangement may be to maintain a specially ventilated area in the testing department for isolation patients.

14.3 Any parts of the system that come into contact with the subject should be disposable or sterilized between patients. If sterilization is not feasible, then high-level disinfection should be performed. [36] All cleaning should comply with manufacturer recommendations. Several pneumotachometers and/or valving assemblies may be required if cleaning cannot be performed in a timely manner between patients.

14.4 The use of bacterial filters is controversial. [118]

14.4.1 Attachment may result in added system dead space and may invalidate pneumotachometer accuracy by increasing total system resistance of the apparatus.

14.4.2 Filter resistance should be subtracted from Raw (and related parameters)

14.4.3 If filters are used in gas-dilution procedures, their volume should be subtracted when FRC is calculated. [24]

Infant/Toddler PFT Guidelines Steering Committee:
Stephanie D Davis, MD, Chairman, Chapel Hill NC
Robin C Johnson RRT, Chairman, Chapel Hill NC
Robert L Flucke RRT, Columbus OH
Jeffrey A Kisling RRT, Indianapolis IN
Timothy R Myers RRT, Cleveland OH

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