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MINI-SYMPOSIUM: LUNG FUNCTION IN PRESCHOOL CHILDREN

Forced oscillations, interrupter technique and body plethysmography in the preschool child

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Summary The interrupter technique, forced oscillation and plethysmography have been increasingly used to monitor early childhood respiratory diseases over the past 30 years. The techniques are based on different principles but generally yield concordant information. Data from all three techniques indicate significant airway response to bronchodilators in healthy and asthmatic preschool children. The interrupter technique is useful but yields little more than a single value of respiratory resistance. Forced oscillation and plethysmography may provide additional information relevant to the mechanisms of airway obstruction, provided the methodological artefacts are accounted for and corrected.

INTRODUCTION

The high incidence of paediatric respiratory diseases has stimulated development of lung-function testing in the preschool child. The purpose of developing methodologies in this context is to answer three practical questions. Is airway obstruction present? If yes, is it reversible? If no, are the airways hyper-responsive to bronchoconstrictor stimuli? The interrupter technique, the forced oscillation technique and body plethysmography all have the potential to disclose some of the relevant information. The principles of these techniques were first described in the middle of the last century.[1–3] However, they have only recently gained access to the paediatric lung-function laboratory, thanks to considerable progress in equipment hardware and computerisation. The techniques are particularly suitable for application in the young child because they are non-invasive and do not demand repeatable respiratory manoeuvres such as forced expiration. The measurement can take place once the child is accustomed to breathing regularly for a few seconds through a mouthpiece wearing a nose clip. In this review, the three methods are compared from the point of view of their background and principle, how this translates into measurement, their methodology and their potential role in diagnosing and understanding diseases such as asthma in the preschool age group.

BACKGROUND AND PRINCIPLES

The term resistance is familiar to the paediatric pulmonologist and usually recognised as the ratio of the pressure difference between two points of the respiratory system in association with air flow (V′). The pressure difference may be measured between the airway opening (Pao) and the body surface (PBS). During spontaneous breathing, there is no measurable difference between Pao and PBS because the pressure generated by the respiratory muscles (Pmus) matches that necessary to overcome the mechanical load of the respiratory system (Prs):

$$Pao - P_{BS} = Pmus + Prs \quad (1)$$

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As Prs combines what is needed to overcome elastic and resistive loads (respectively, Pel,rs and Pres,rs):

$$\text{Pao} - \text{P}_{\text{BS}} = \text{Pmus} + \text{Pel, rs} + \text{Pres, rs} \quad (2)$$

and, assuming Poiseuille's law:

$$\text{Pao} - \text{P}_{\text{BS}} = \text{Pmus} + \text{Pel, rs} + \text{Rrs} \cdot \text{V}' \quad (3)$$

Rrs is the resistance of the respiratory system.

For Pres,rs to show, one may briefly interrupt V' and, since V' = 0, eq. 3 reads:

$$\text{Pao} - \text{P}_{\text{BS}} = \text{Pmus} + \text{Pel, rs} \quad (4)$$

by subtraction of eq.(4) from eq.(3):

$$\Delta(\text{Pao} - \text{P}_{\text{BS}}) = \text{Rrs} \cdot \text{V}' \quad (5)$$

This estimate of Rrs is known as the interrupter resistance (Rrs_{int}) given by:

$$\text{Rrs}_{\text{int}} = \Delta(\text{Pao} - \text{P}_{\text{BS}})/\text{V}' \quad (6)$$

It is also possible to artificially create an external mechanical load and generate flow, independent of the respiratory muscles. This is much the same situation as when a mechanical ventilator moves the chest of a patient. Because the driving pressure has the form of a sinusoidal wave at a frequency of 5–30 Hz, this method is called the forced oscillation technique (FOT). The pressure generated externally is equal to Prs which, using the definition at spontaneous breathing frequency and adding the inertial pressure component (Pin,rs) present at high frequency, is given by:

$$\text{Pao} - \text{P}_{\text{BS}} = \text{Pel, rs} + \text{Pin, rs} + \text{Pres, rs} \quad (7)$$

The resulting flow is also a sine wave, the amplitude and phase of which depends on respiratory elastic, inertial and resistive properties. Dividing the pressure sine wave by the flow sine wave yields a complex quantity called the respiratory impedance, where Pres,rs / V' resembles the expression in eq. (5) and yields another estimate of resistance, the forced oscillation resistance (Rrs_{fot}):

$$\text{Rrs}_{\text{fot}} = \text{resistive part of } (\text{Pao} - \text{P}_{\text{BS}})/\text{V}' \quad (8)$$

The resistive part of Pao − P_{BS} is the component of the pressure which is in phase with the flow; Rrs_{fot} may be obtained either graphically or from the amplitude and phase relationships of the two signals. Information on the apparent elasticity of the respiratory system may be derived from the part of the respiratory impedance called respiratory reactance. The mechanical behaviour of the respiratory system may be studied simultaneously at different driving frequencies.[4–6] Alternatively, at a single frequency, FOT allows the study of changes in airway dimensions with time.[4]

Body plethysmography allows the non-invasive measurement of alveolar pressure (Palv). When a subject breathes inside the body box, volume compression or displacement occurs. This change (ΔV_{plet}) is small and is in proportion to the compressibility of the thoracic gas volume (TGV) — also called gas compliance (Cg) — and to the pressure difference between the alveoli and the airway opening (Palv − Pao).

Therefore:

$$\Delta\text{V}_{\text{plet}} = \text{Cg} \cdot (\text{Palv} - \text{Pao}) \quad (9)$$

Using Boyle's law to express Cg (TGV/barometric pressure, PB) and Poiseuille's law to express airway resistance (Raw = (Palv − Pao) /V'):

$$\Delta\text{V}_{\text{plet}} = \text{TGV} \cdot \text{Raw} \cdot \text{V}'/\text{PB} \quad (10)$$

Rearranging:

$$\text{Raw} \cdot \text{TGV} = \text{PB} \cdot \Delta\text{V}_{\text{plet}}/\text{V}' \quad (11)$$

The product of Raw and TGV is known as the specific Raw (sRaw). It is the usual end-point of plethysmographic measurement in preschool children, as they are usually unable to perform the respiratory manoeuvre against closed shutter which is necessary to measure TGV and subsequently calculate Raw.

In summary, the three techniques have the potential for useful information on airways patency. These estimates of resistance vary with tidal volume and flow and change between inspiration to expiration particularly because of upper airway dynamics. Because of the different pressures being estimated, Rrs_{int} and Rrs_{fot} contain information related to the lung and the chest wall whereas sRaw relates to the airways and absolute lung volume.

REAL LIFE

When translating the principle into a measurement, each has its own methodological peculiarities and limitations. Some limitations may be addressed by the following questions: Does the measured pressure difference correctly estimate resistive pressure? Does the measured flow only reach the airway lumen? Is the relationship between resistance and flow linear?

Does the measured pressure difference correctly estimate resistance?

With the interrupter technique, it is assumed that the change in Pao only relates to flow cessation (eq. 5). For the assumption to be valid, Pao (eq. 4) should be measured at the interruption. However, it takes several milliseconds for the shutter to close and the closure is associated with pressure transients. Thus Pao is obtained by extrapolating the stable part of the pressure signal, through the pressure oscillations, into the time of zero flow. Pressure equilibration within the airways is not instantaneous, particularly in the presence of heterogeneous airway obstruction. Should Pmus change as a result of an active expiration, (a likely possibility in the presence of airway obstruction), the assumption that the change in Pao before and after the