

A flow interruption device for measurement of airway resistance

P.J. Chowieniczky*, C.P. Lawson*, S. Lane*, R. Johnson*, N. Wilson**,
M. Silverman**, G.M. Cochrane*

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ABSTRACT: Unlike conventional methods, the interrupter method for measuring airway resistance is non-invasive and requires minimal patient co-operation. It can therefore be applied in critically ill patients, acute asthmatics, neonates, pre-school children, geriatric patients and unconscious patients.

The method is based on transient interruption of airflow at the mouth for a brief period during which alveolar pressure equilibrates with mouth pressure. Measurement of mouth pressure is used to estimate alveolar pressure prior to interruption and the ratio of this to flow prior to interruption gives airway resistance. Using the interrupter method we have developed a portable device for measuring airway resistance which is simple to use and gives a direct instantaneous reading.

Measurements of airway resistance obtained using the new device were compared with those obtained using conventional body plethysmograph methods in 43 adult patients. A close correlation was seen ($r=0.86$). The two methods appear equally sensitive in detecting changes in airway resistance following bronchodilator therapy. The device has been used successfully in pre-school children unable to co-operate with conventional methods.

Eur Respir J, 1991, 4, 623-628.

* Dept of Respiratory Medicine, Guy's Hospital, St. Thomas' Street, London, UK.

** Dept of Respiratory Paediatrics, Royal Post Graduate Medical School, Hammersmith Hospital, Du Cane Road, London, UK.

Correspondence: Dr G.M. Cochrane, Dept of Respiratory Medicine, Guy's Hospital, St Thomas' Street, London, SE1 9RT, UK.

Received: March 23, 1990; accepted after revision, December 10, 1990.

Keywords: Airway occlusion; interrupting valve; transient pressure response.

Conventional methods used to assess airway resistance (R_{aw}) require a relatively high degree of patient co-operation. This precludes their use in important groups of patients: neonates, pre-school children, the critically ill, comatose patients and some geriatric patients. In contrast the "airway occlusion" or "interrupter" method has the potential to provide measurements of airway resistance and requires minimal patient co-operation. The idea behind the interrupter method is that during transient interruption of airflow alveolar pressure will equilibrate rapidly with pressure at the mouth. Measurement of mouth pressure immediately post-occlusion will therefore give alveolar pressure. Provided that occlusion is sufficiently rapid alveolar pressure immediately after occlusion will approximate alveolar pressure immediately prior to occlusion. The ratio of this pressure to flow rate at the time of occlusion is the airway resistance as determined by the interrupter technique (Rint). This theory is rather simplistic since, in reality, the inertia of gas in the airways and the compliance of the airways results in a delay in equilibration of pressure across the bronchial tree and an oscillation of the pressure transient. Nevertheless, an estimate of alveolar pressure can be

obtained by measuring mouth pressure some time after airway occlusion and back extrapolating to a time close to the time of occlusion [1, 2].

The interrupter method has not been widely used, partly because the equipment required is technically difficult to produce and partly because of theoretical reservations regarding the validity of the method. Recent theoretical analysis by BATES and co-workers [3, 4] suggests that the method is essentially valid, although upper airway compliance may cause Rint to underestimate the true value of airway resistance. Upper airway compliance can be minimized by supporting the cheeks and pharynx. Experimental work in dogs by BATES *et al.* [5] shows that in open-chested dogs Rint is an excellent approximation to R_{aw} even in the presence of parallel heterogeneity. In closed-chested dogs Rint is strongly correlated with R_{aw} even in the presence of bronchoconstriction, but includes a contribution from the chest wall, and therefore tends to exceed R_{aw} [6, 7]. In view of this recent theoretical and animal work and the important practical advantages of the method, we have developed a new device for assessing airway resistance based on the interrupter method. The instrument is particularly simple to use, requires no

co-operation by the patient, is portable and provides a direct instantaneous measurement of airway resistance. We describe the design of the new device and results of a preliminary validation.

Design

The new device consists of an interrupting valve and transducer unit connected to a custom miniature computer (fig. 1). The transducer head connects to the airway *via* either a face mask or mouthpiece. Design of the transducer head (fig. 2) facilitates accurate measurement of R_{int} by achieving rapid airway occlusion and high fidelity recording of the pressure transient. The pressure sensor is a piezoelectric element (Sensor Technics, Rugby, UK) and is connected to the airway with a deadspace of less than 0.2 ml. This ensures

accurate recording of pressure transients at frequencies up to 500 Hz. Interposition of a flow-resistive mesh between pressure sensor and interrupting valve generates a pressure dependent on flow. When the interrupting valve is open, airway flow can be measured as a function of recorded pressure. The interrupting valve consists of a lightweight elliptical plate driven to occlude the lumen of a tube. Forces on the occluding plate generated as a result of airflow are balanced, so that only minimal force is required to move the plate. Use of an elliptical rather than a circular plate eliminates frictional forces between the plate surfaces and tube lumen when the valve is closed. This again reduces the force required to drive the valve. A high speed servomotor is used to drive the plate (Interelectric AG, Sachseln, Switzerland). A rapid speed of the occlusion is achieved (approximately 5 msec), reducing artefacts due to valve closure time [8]. Leakage through the valve when subjected to a pressure head of 2 kPa is less than $0.001 \text{ l}\cdot\text{s}^{-1}$ (equivalent to a resistance greater than $2,000 \text{ kPa}\cdot\text{l}^{-1}\cdot\text{s}$). The valve is lightweight, requires minimal electrical power and is unobtrusive in use. Control signals to the interrupting valve and the analogue signal from the pressure transducer are passed to a dedicated computer comprising a single chip microcomputer, analogue to digital converter, liquid crystal display, graphics printer and miniature keyboard.



Fig. 1. — The new device for measuring airway resistance consists of a transducer unit and dedicated miniature computer. The transducer unit connects to the airway by either a mouthpiece or face mask.

Operation and signal analysis

With the interrupter valve open, pressure and hence flow is continuously monitored. When flow reaches a predetermined value (usually $0.5 \text{ l}\cdot\text{s}^{-1}$) the valve is actuated. For the next 100 msec pressure values are stored in the memory at intervals of 1 msec. Approximately 5 msec after the valve is actuated complete airway occlusion is achieved. The valve is held in the closed position for a further 100 msec. This period of airway occlusion is virtually imperceptible to the patient.

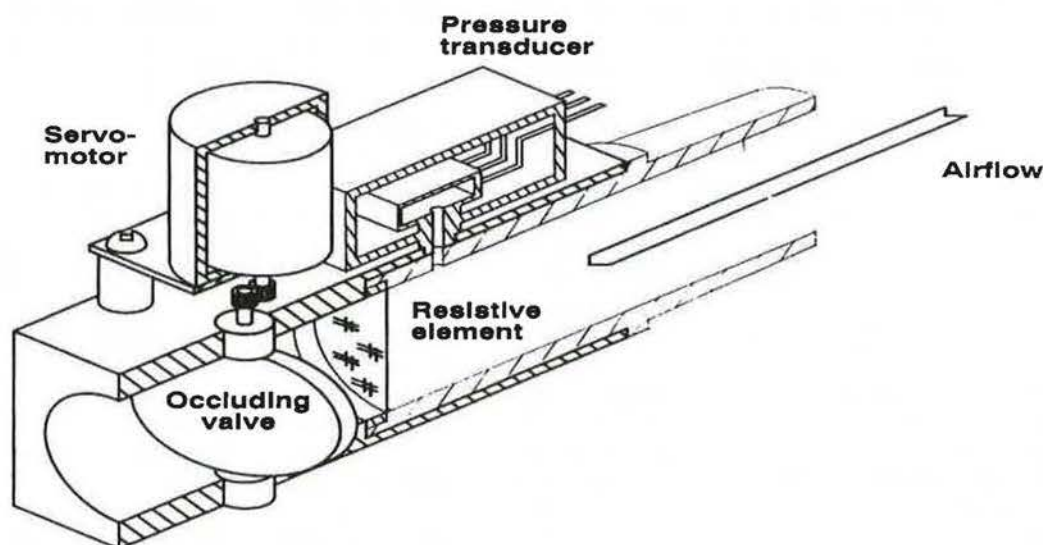


Fig. 2. — Schematic section through the transducer unit demonstrating pressure transducer, flow resistive element and airway occluding valve.

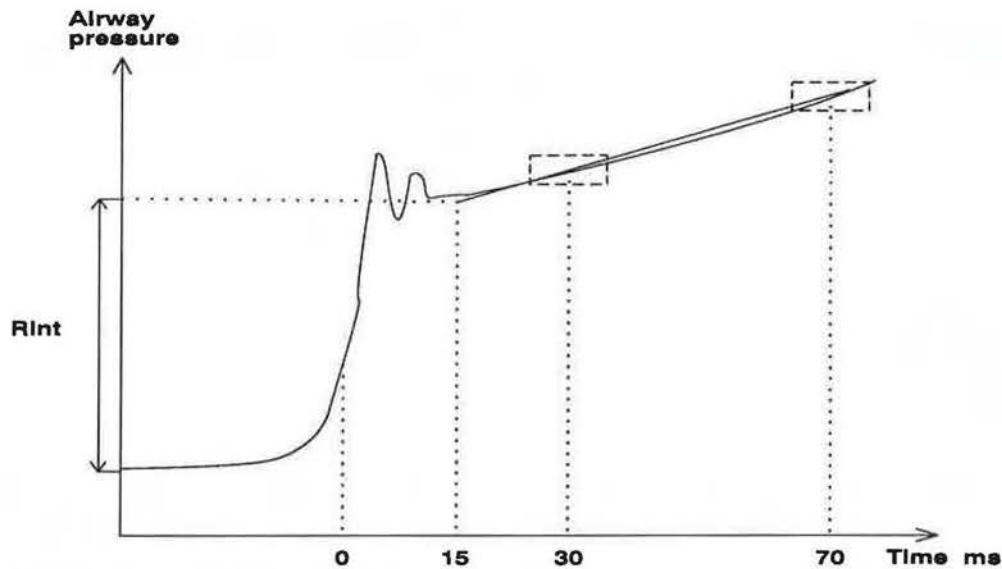


Fig. 3. — Airway resistance as determined by the interrupter technique (Rint) is computed by back extrapolating a line drawn through two points which are block averages of pressure over 10 msec.

The valve is then opened and the stored pressure transient analysed to compute Rint (fig. 3). The time of airway occlusion (t_o) is defined as that at which the pressure signal reaches 25% of the difference between the maximum value of the first clearly defined peak of pressure oscillations and the baseline value. The signal is then averaged over two 10 msec time periods, the first centred on a time (t_o)+30 msec and the second on a time (t_o)+70 msec. These two average values are used to back-extrapolate the pressure transient to a time (t_o)+15 msec. The difference between the back-extrapolated pressure and the baseline pressure immediately prior to interruption is taken as the alveolar pressure at the time of interruption and Rint as the ratio of this pressure to flow at the time of interruption. A switch allows reversal of the polarity of the pressure signal (and hence the flow signal) and allows measurements to be made in inspiration or expiration as desired. An adaptor allows the transducer head to be connected directly to a manometer for pressure calibration. Flow calibration is achieved by passing a reference flow through the transducer head. In the experiments described, reference flows were measured using a rotameter (Fisher Controls, Croydon, UK).

Evaluation

Measurements of Rint were compared with measurements of airway resistance obtained using the body plethysmograph (Raw) in 43 adult patients with varying degrees of airflow obstruction (forced expiratory volume in one second (FEV₁) ranging from 19–107%). Seventeen of these patients were diagnosed to have reversible airways obstruction. In these patients measurements of Rint and Raw were performed before and after administration of a bronchodilator (800 µg of salbutamol). For the measurement of Rint patients breathed through a

mouthpiece with the nares occluded and were asked to support their cheeks and pharynx. Measurements were taken during tidal breathing at a flow rate of 0.5 l·s⁻¹ in inspiration. We chose to measure Rint during inspiration to avoid problems associated with airway collapse during expiration. Raw was computed using an automated method [9] which calculates an average value for inspiratory and expiratory airway resistance from pressure and flow measurements obtained whilst the patient performs rapid shallow breathing ("panting") [10]. In each patient spirometric measurements were followed by 6 measurements of Raw and 12 measurements of Rint. In patients who were given a bronchodilator, a further 6 measurements of Raw and 12 of Rint were performed approximately 15 min after administration of the bronchodilator. Mean values of Raw and Rint were used in the analysis of results.

We also performed a preliminary evaluation in 10 pre-school children (three year olds) who were unable to perform any other test of respiratory function. As part of a separate ongoing study (for which full Ethical Committee approval had been granted) the response to airway challenge was being assessed indirectly by measuring transcutaneous oxygen tension (PtcO₂). In each 3 yr old, 6 measurements of Rint were obtained as a baseline and 6 measurements were made after methacholine challenge. A further 6 measurements were then made after administration of a bronchodilator. The children breathed through paediatric face masks with an air cushion seal and were thus able to nose or mouth breathe. Rint was measured at a flow threshold of 0.2 l·s⁻¹. The presence of a significant leak through the mask was assessed by inspecting the pressure-time waveform; the effect of a leak being to reduce initial high frequency oscillations in the pressure transient. In practice we found that once the correct size of mask was selected and the child was used to the mask being firmly held, leaks did not occur.

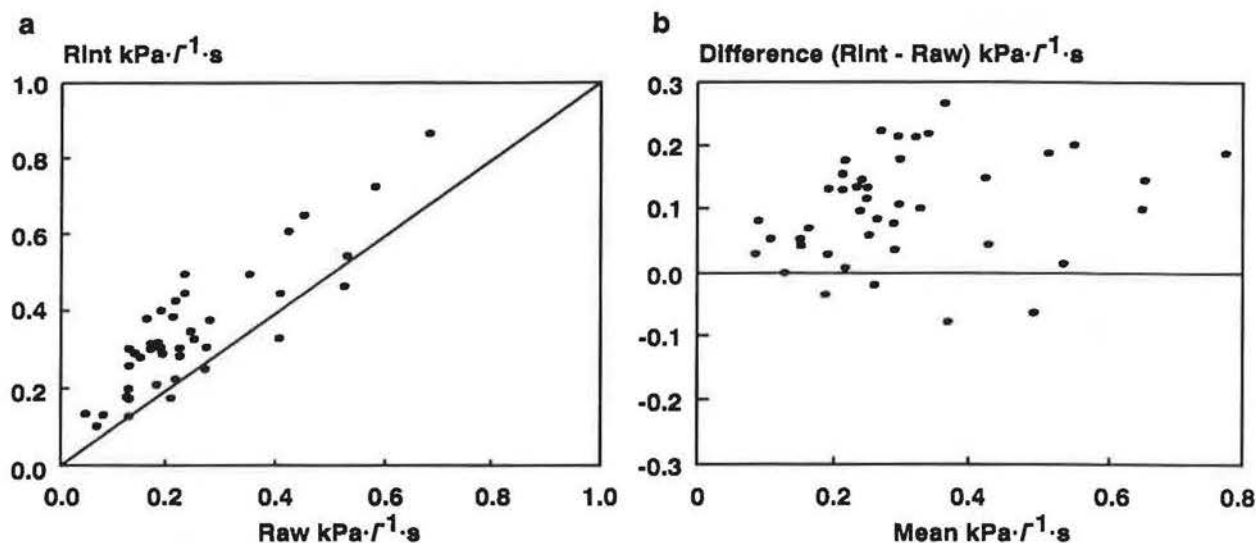


Fig. 4. — a) Relationship between airway resistance measured using the interrupter technique (Rint) and the body plethysmographic technique (Raw). The solid line is the line of identity. b) Difference between Rint and Raw (Rint - Raw) versus mean value of resistance ((Rint+Raw)/2).

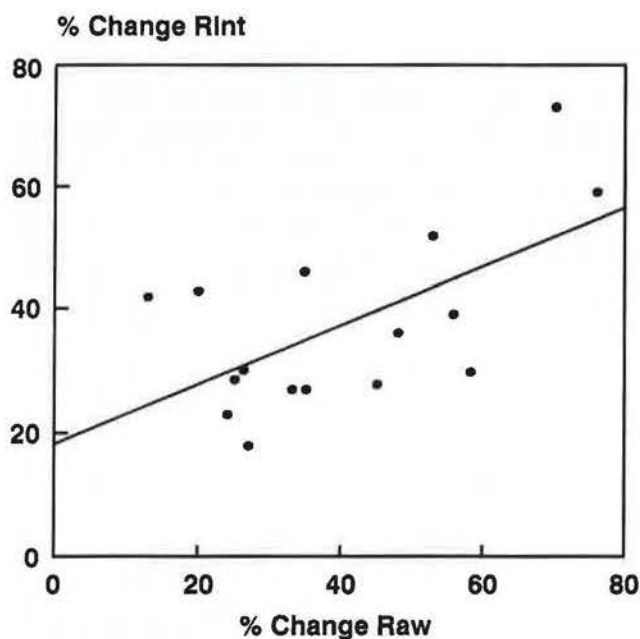


Fig. 5. — Percentage change in Rint following bronchodilator versus percentage change in Raw. The solid line is the regression line. For abbreviations see legend to figure 4.

Results

In the adult subjects there was a close correlation between Rint and Raw ($r=0.86$, fig. 4a). When analysed in terms of differences about the mean (fig. 4b) substantial differences were apparent, with Rint exceeding Raw in most cases (mean difference $0.10 \text{ kPa}\cdot\text{l}^{-1}\cdot\text{s}$, standard deviation of the difference $0.082 \text{ kPa}\cdot\text{l}^{-1}\cdot\text{s}$). Breath-to-breath variation in consecutive measurements of Rint tended to be higher (mean coefficient of variation (CV) 16.3%, range 5–43%) than variation in consecutive readings of Raw (mean CV

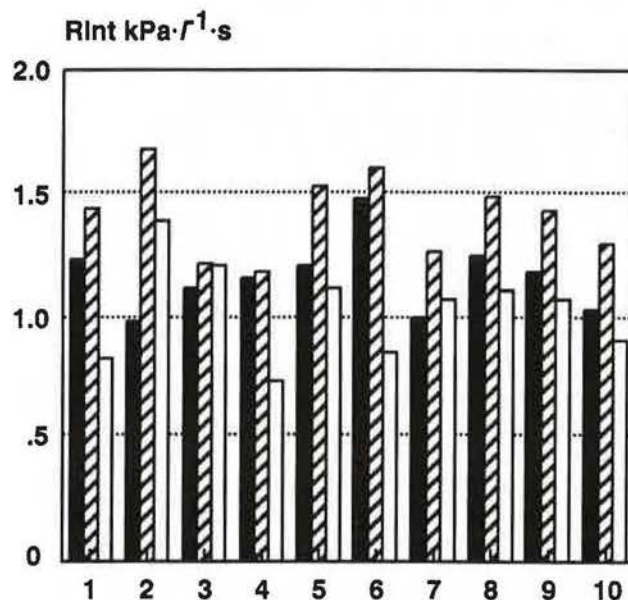


Fig. 6. — Changes in mean values of Rint following methacholine and salbutamol in ten 3 yr olds. ■ : Baseline; ▨ : Methacholine; □ : Salbutamol. For abbreviations see legend to figure 4.

13.2%, range 1–54%). Percentage changes in Rint and Raw after bronchodilation are compared in figure 5. Following bronchodilation, the mean change in Raw (39%) was not significantly different from the mean change in Rint (37%). Changes in Raw were significant (t-test, $p<0.05$) in 16 of the 17 subjects. Changes in Rint were significant in all 17 patients.

In the acceptability study on 3 yr olds we found that all 10 were able to use the device. In each of the subjects an increase in Rint was seen following methacholine and a decrease following bronchodilator (fig. 6).

Discussion

The objectives of the present study were firstly to compare measurements of Rint obtained using the new device with measurements of Raw obtained using the plethysmograph. Secondly, to assess the feasibility of using the new device in patients unable to co-operate with conventional respiratory function tests based on the forced expiration. We obtained a close correlation between Rint and Raw in adult patients. Changes in Rint following a bronchodilator were similar to those in Raw and the average percentage change (over all patients) was within 2%. This suggests that the device should be useful in detecting changes in airway resistance following therapeutic intervention.

Differences between Rint and Raw in individual subjects were substantial. However, absolute agreement between the two methods cannot be expected. We chose to measure Rint in the inspiratory phase of normal breathing to avoid problems of airway collapse which may occur in patients with airflow obstruction. The method used for measuring Raw gives an average of inspiratory and expiratory resistance over the whole breathing cycle. Furthermore, Raw is measured during rapid shallow breathing. This manoeuvre reduces the contribution of the glottis to overall airway resistance [11]. The body plethysmograph is used mainly for measuring small changes in airway resistance in normal subjects. In these circumstances it is desirable to reduce the contribution of the glottis, as it can be as much as 50% of the total airway resistance [12]. In situations where there is a significant degree of airway narrowing the resistance of the glottis is less important. Inclusion of a component of upper airway resistance and a component of lung tissue and chest wall resistance [6, 7] may explain why values of Rint are slightly higher than those of Raw. A comparison of Rint with Raw measured under identical conditions is problematic. During tidal breathing the DuBois method becomes inaccurate due to thermal effects involving cooling and condensation of water vapour in expiration and warming and humidification of air in inspiration [13]. In patients with airflow obstruction, the alveolar pressure-flow relationship from which Raw is calculated becomes influenced by many factors other than airway resistance [9, 13]. These are partly allowed for by the method we use which measures both inspiratory and expiratory resistance.

Unlike current methods for assessing airway resistance the new device does not require patient co-operation. Children too young to co-operate with conventional tests of respiratory function find no difficulty in breathing through a mask. All 10 of the 3 yr olds that we tested were able to use the device. Few of these children were able to co-operate with the forced oscillation technique and none with forced expiratory respiratory function tests. The study was intended as an acceptability study and the timing of measurements before and after administration of methacholine and salbutamol could not be tightly controlled, possibly blunting the changes in airway resistance which we observed. Nevertheless, in each three year old we

observed an increase in Rint after methacholine and a decrease after salbutamol (fig. 6).

The only other technique which does not involve a high degree of active co-operation is the forced oscillation technique [14, 15]. However, this technique does involve the patient maintaining a patent upper airway for several seconds. This can be surprisingly difficult for many patients, particularly young children to achieve. Rint is measured during spontaneous airflow during which momentary closure of the glottis does not occur. The equipment involved is also bulky and cannot be developed into a portable instrument.

The form of the algorithm used to back extrapolate mouth pressure to obtain Rint requires further evaluation. BATES *et al.* [2] have suggested a more sophisticated exponential extrapolation procedure. In cases where the site of resistance lies upstream (on the alveolar side) of a compliant compartment, back extrapolation has been shown to lead to an underestimation of the true resistance [4]. Airway compliance of the upper airway and lower order airway generations can therefore be expected to lead to an underestimation of resistance when back extrapolation to the time of occlusion is used. In adults Rint was largely insensitive to the exact point of back extrapolation. However, in the three year olds this was not the case, perhaps reflecting a higher upper airway compliance. In these subjects the form of the algorithm becomes more critical and requires further investigation.

In conclusion, the new device provides a simple, portable means for measuring airway resistance. Results from our preliminary evaluation are encouraging and suggest that the device has potential for obtaining measurements in patients too young or too ill to co-operate with conventional methods.

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Un dispositif d'interruption du flux pour la mesure de la résistance des voies aériennes. P.J. Chowienczyk, C.P. Lawson, S. Lane, R. Johnson, N. Wilson, M. Silverman, G.M. Cochrane.

RÉSUMÉ: A l'opposé des méthodes conventionnelles, la méthode d'interruption pour la mesure de la résistance des voies aériennes est non invasive et ne demande qu'une coopération minimale de la part du patient. Elle peut dès lors être appliquée à des malades en état grave, à des asthmatiques en crise, à des nouveau-nés, aux enfants en âge pré-scolaire, aux patients gériatriques ou inconscients.

La méthode est basée sur une interruption transitoire du courant aérien au niveau de la bouche, pour une brève période au cours de laquelle la pression alvéolaire s'équilibre avec la pression buccale. La mesure de la pression buccale est utilisée pour estimer la pression alvéolaire avant l'interruption, et le ratio de celle-ci au débit préalable à l'interruption donne la résistance des voies aériennes. En utilisant la méthode d'interruption, nous avons développé un instrument portable pour la mesure des voies aériennes, qui est d'usage aisé et donne une lecture directe instantanée.

Les mesures de la résistance des voies aériennes obtenues au moyen de ce nouveau dispositif ont été comparées à celles obtenues par la pléthysmographie corporelle conventionnelle chez 43 adultes. Une relation étroite relie les deux valeurs ($r=0.86$). Les deux méthodes s'avèrent également sensibles pour la détection des modifications de résistance des voies aériennes à la suite d'un traitement bronchodilatateur. Le dispositif a été utilisé avec succès chez les enfants en âge pré-scolaire incapables de coopérer en cas d'emploi des méthodes conventionnelles.

Eur Respir J., 1991, 4, 623-628.