THE HALOSCALE "INFANTA" WRIGHT RESPIROMETER
An In Vitro and In Vivo Assessment

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The Wright respirometer [1] has been used for many years for the measurement of tidal and minute volumes in adults and children of 20 kg body weight and over. As with any turbine instrument, performance decreases markedly at low gas flow rates. The recently-introduced Infanta turbine contains modifications designed to increase the sensitivity of the instrument so as to produce a simple device for measuring volume in infants and children, and in any patient with severe ventilatory weakness.

The purpose of this study was to assess the performance of this device in vitro and in vivo, and to verify its working range.

MATERIALS AND METHODS

The Infanta instrument (Ferraris Medical Ltd) was designed primarily for the measurement of ventilation in infants with tidal volumes of as little as 15 ml, and not for measuring continuous gas flows. Increased sensitivity was achieved in four ways. First (fig. 1), a barrier was placed across the outer gallery of the turbine (1) so that the flow of gas cannot divide and stagnate on the side opposite the point of entry. Second, the slots in the stator (2) through which gas passes to reach the rotor vane were reduced in length compared with the adult instrument, and graduated so that each slot gives an equal impulse to the vane. Third, the deadspace of the instrument was decreased to 14 ml by filling much of the gallery around the exterior of the stator (3). The principle of the barrier was proposed by Professor S. P. Hutton, who with Dr J. A. Bushman and one of the authors (G.W.) contributed the graduation of the slots and reduction of deadspace. The dividing of the dial was also altered (by G.W.) so that it effectively increases the reading sensitivity whilst conveniently retaining the same gear ratio used in the standard instrument. Calibration jets were chosen which cause a percentage of the flow to bypass the slots in the stator and enable accurate calibration, as in the standard model, but a finer degree of adjustment is required to achieve the stated performance.

Resistance is 0.24 kPa litre\(^{-1}\) s at 15 litre min\(^{-1}\).

Methods of testing: in vitro

Volume studies. The apparatus used to determine the volume calibration of the Infanta respirometer (fig. 2) was a modification of the ventilator performance recording system described by Newton, Hillman and Varley [2] using the same ISO test compliances (a) and resistances (b), kindly loaned by Dr Newton, to simulate infant pulmonary conditions. The smallest Starling pump (stroke volume 0–200 ml) was used instead of the Nuffield ventilator and Newton value. The volume between the pump and the test lung was 54 ml.

The volume registration of the Infanta was...
calibrated against the volume swept per stroke by the Starling pump piston. To verify that there were no leaks in the system, the output of the Starling pump was compared with the geometrically integrated volume from the flow signal of a Mercury Electronics pneumotachograph type F100L (c) connected to a Mercury Electronics differential pressure transducer type M7 (d). The output from this transducer was recorded on a Kipp and Zonen chart recorder type BD8 (e). The pneumotachograph was assessed for linearity, and calibrated over the range 0–100 litre min\(^{-1}\) in each direction using automatically timed constant flows passed into a dry gas meter which had been calibrated previously at 16 and 60 litre min\(^{-1}\) by reference to an absolute gas holder (Parkinson and Cowan No. 1112).

Volume measurements were obtained by measurement of the area between the flow signal and zero flow line. Simultaneous tidal volume measurements were obtained from the Infanta respirometer and the pneumotachograph using the mean volume of 10 successive pump strokes. Frequency was varied stepwise between 25 and 60 min\(^{-1}\), for tidal volumes between 15 and 200 ml.

**Flow studies.** When the instrument had been calibrated by reference to known simulated tidal volumes, the respirometer was subjected to a range of continuous flows from 1 to 20 litre min\(^{-1}\). At 1 and 2 litre min\(^{-1}\) the volume registered was compared with flow passed through an accurate flowmeter (Rotameter Mfg. Co: Serial No. 817481/61; range 0.3–3 litre min\(^{-1}\). With flows greater than 2 litre min\(^{-1}\), the comparison was with the volume passed through the dry gas meter described above, while time was measured electronically.

**Methods of testing:** in vivo.

Simultaneous measurements of tidal volume were obtained from the Infanta respirometer and a pneumotachograph placed in series in the breathing system in infants and young children.
after the induction of general anaesthesia for ophthalmic surgery. Measurements were made on 48 occasions in 13 patients breathing spontaneously and on 32 occasions in 13 patients during intermittent positive pressure ventilation (IPPV). Patients’ ages ranged from 2 days to 8 yr and their weights from 2.74 to 23.1 kg. Tracheal intubation had been facilitated by suxamethonium in all patients before the measurements. The pneumotachograph and respirometer were positioned within the apparatus deadspace in spontaneously breathing patients with the spirometer inserted to record expired volume, and in the inspiratory limb of the ventilator during IPPV. The pneumotachograph used was a Fleisch flowhead (heated to 37 °C) connected to a Validyne differential pressure transducer (Model MP45). Full details of the accuracy of this recording system have been reported elsewhere [3]. Volume was integrated electronically from the flow signal and results stored on a Racal Store 4 tape recorder for output later on a u.v. paper recorder (SE laboratories, Model 3006). The mean value was taken from five breaths and peak flow rates were noted during each measurement. The accuracy of the system was checked against the Mercury Electronics system using the ventilated test lungs described above. The calibration of the Infanta was confirmed before, during and after the series of studies.

RESULTS

In Vitro

Volume studies. The results obtained with the apparatus shown in figure 2 demonstrated that the Infanta registered volumes from the Starling pump within the range 15–200 ml with an accuracy of ±5%. The registered volume decreased rapidly below 15 ml, whilst over-registration developed rapidly above 200 ml.

Flow studies. The results of the continuous flow studies are shown in figure 3. The response was not linear, but was in principle, similar to that exhibited by any inferential turbine flowmeter. The turbine is required by the manufacturers to respond before the flow exceeds 1.1 litre min⁻¹.

The continuous flow performance of the Infanta turbine was of a nature similar to that established [4] for the standard Wright respirometer, but with more than two and a half times the sensitivity.

![Continuous flow performance of the Infanta turbine compared to the Wright respirometer.](https://academic.oup.com/bja/article-abstract/60/2/232/259640/fig3)
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Fig. 4. Comparison of tidal volumes recorded by Infanta respirometer and pneumotachograph during spontaneous ventilation: 48 measurements in 13 children, shown in relation to the line of identity.

Fig. 5. Comparison of tidal volumes recorded by Infanta respirometer and pneumotachograph during intermittent positive pressure ventilation: 32 measurements in 13 children, shown in relation to the line of identity.

overall. The curve is asymptotic beyond 8 litre min\(^{-1}\) to 20% less than the absolute continuous flow passing through the instrument. This results from the choice of division of the scales of the instrument already referred to, so that although 400 ml has passed per revolution, the divisions cover 500 ml. The effect is to enhance the reading sensitivity in the ratio of 5:4 by providing compensation of that fixed magnitude overall for what would otherwise appear as under-reading.

In vivo

Tidal volume. Figures 4 and 5 show the results from the respirometer and pneumotachograph in relation to the line of identity for spontaneous ventilation (SV) and IPPV. Plots of the difference between the methods against their mean values are shown in figures 6 and 7. The mean difference during SV was 2.15 ml, with 95% confidence limits for the bias of \(-0.07\) and \(+4.37\) ml. The overall 95% confidence limits of agreement between the two methods, when analysed as suggested by Bland and Altman [5] were \(-9.09\) and \(+13.39\) ml. During IPPV the mean difference between the methods was \(3.08\pm2.18\) ml, and the overall limits of agreement were \(-7.89\) and \(+14.05\) ml. Peak flow rates ranged from 1.9 to 20 litre min\(^{-1}\).

The smallest tidal volume recorded by the Infanta was 4.7 ml, corresponding to a measurement of 8.2 ml from the pneumotachograph. This suggests that, as ventilation decreases to the threshold, the instrument under-reads and is, therefore, safe in use.

DISCUSSION

It has been known for many years [6] that, while there is a relationship between minute volume and body weight in infants, this relationship is different for premature as opposed to full-term infants, and that the range of normal data for any particular body weight is large.

Before the introduction of the Infanta respirometer, there had been no reliable mechanical device suitable for the measurement of tidal volume in infants and young children weighing less than 20 kg. Although accurate pneumotachographs are available for this purpose, the complex nature of their calibration procedures, together with the bulk of the equipment, and the problem of drift from the electronic integration of the flow signal, makes it unlikely that they will ever become popular for routine clinical measurement. In addition, it is well known that the resistance of these devices is easily increased by the accumula-
Fig. 6. Difference between tidal volumes obtained with the pneumotachograph ($V_p$) and Infanta respirometer ($V_r$) plotted against average tidal volume using the two methods. Results in the 13 patients studied during spontaneous ventilation. (Mean ± 2SD lines drawn.)

Fig. 7. Difference between tidal volumes obtained with the pneumotachograph ($V_p$) and Infanta respirometer ($V_r$) plotted against average tidal volume using the two methods. Results in the 13 patients studied during intermittent positive pressure ventilation. (Mean ± 2SD lines drawn.)

tion of dirt or the condensation of water vapour on the flow-head. The adult Wright respirometer was thoroughly evaluated by Nunn and Ezi Ashi [4]. They showed that its accuracy was adequate for clinical purposes, a finding which has since been confirmed in more than 20 years of clinical experience. The device, however, under-reads at low flows, such that the lower limit of its accurate working range is at a minute volume of approximately 5 litre. Depending upon the waveform, this represents an error within 10% at minute volumes greater than 3 litre, 5% above 4 litre and 3% above 5 litre. Normal data for minute volume in children [7] show that the adult respirometer will therefore be clinically useful above a body weight of approximately 20 kg.

At the cost of proportionally increasing resistance to gas flow, a reduction in the number and the cross-sectional areas of the slots in the cylindrical stator of the respirometer turbine will increase its sensitivity to a given volume (mass) rate of gas flow. The results of the present study show that the modifications introduced with the Infanta respirometer have increased its sensitivity
overall by three times when compared with the standard Wright respirometer, whilst retaining the inherent simplicity and unidirectional flow properties of the traditional respirometer turbine. External size is similar.

Resistance remains lower (0.24 kPa litre\(^{-1}\) s at 15 litre min\(^{-1}\)) than for other infant respirometers which have been described, and well below the value for non-elastic flow resistance for spontaneously breathing newborn infants [8]. Using Doershuk's data [9], the airways resistance of the largest child in whom this device is likely to be used would be 1.2 kPa litre\(^{-1}\) s, about five times the resistance of the respirometer. The modified Wright respirometer evaluated by Wilkes and colleagues [10] had a resistance of 2.9 kPa litre\(^{-1}\) s at 18 litre min\(^{-1}\) and that produced by Saner and Roth [11] for use in children had a resistance of 0.6 kPa litre\(^{-1}\) s at 10 litre min\(^{-1}\). Wilkes and colleagues [10] noted that the resistance of their respirometer resulted in a decrease in minute volume. Milic-Emili and Tyler [12] showed, in adults, that minute volume decreases as non-elastic resistance to breathing increases.

The validity of using ISO test compliances and resistances was demonstrated by Newton, Hillman and Varley [2], whose method also avoids the very difficult problem of asserting and illustrating the wave-forms of the ventilatory flows.

The results of the in vitro studies show that the Infanta respirometer registered volumes from the Starling pump with an accuracy of ± 5% within the range 15–200 ml. Applying the analysis described by Bland and Altman [5] to the in vivo results shows that, although there are between-method differences between tidal volumes recorded by the Infanta and the pneumotachograph, these differences are clinically acceptable. The errors of pneumotachography have been recognized for many years [13–15] and the difficulties of using this technique in the clinical situation are also well known. The Infanta respirometer, being a simple turbine, overcomes some of these difficulties and appears to be at least as accurate as the pneumotachograph. The 14-ml deadspace and rather large bulk make it unsuitable for continuous use within the apparatus deadspace in small infants.

The capability of any turbine type of instrument to measure tidal volumes accurately cannot be deduced from the continuous flow calibration without knowledge of the wave-form for any particular tidal volume. This explains the discrepancies between Infanta and pneumotachograph volumes put forward by Meeke and co-workers [16] when a small range of volumes was delivered from a calibrated syringe at different flow rates. These authors completely ignored the influence of wave-form, although Bushman [17] clearly demonstrated that the relationship between adult Wright respirometer readings and wave-form was far more complex than could be predicted from measurement of peak flow.

The measurements of continuous flow in the present study (fig. 3) demonstrated that volume registration starts at less than 1.1 litre min\(^{-1}\) compared with 2.5 litre min\(^{-1}\) for the adult turbine. The figure shows the same non-linear response to increasing flow rate when measured under conditions of continuous flow as found for the adult device by Nunn and Ezi-Ashi [4], but with increased sensitivity. Continuous flow data are of use in the initial calibration of new instruments and in recalibration after servicing or repair, but are not analytically readily correlated to tidal volume wave-forms, specifically or in their entirety. No such correlation has been published to date.

For many years neonatologists, paediatric anaesthetists and others involved in the critical care of infants and young children have relied heavily on changes in ventilatory frequency and other clinical signs in the assessment of respiratory failure. Although a few ventilators used in children do contain volume-sensing devices, most machines for paediatric use do not, so that the clinician must rely on chest movement, airway pressure measurements and blood-gas analysis in the assessment of the adequacy of ventilation. Sudden reduction in lung compliance or increase in airway resistance will lead to a reduction in ventilation when pressure generators are used or when there is a deliberately introduced leak in the system, either around the tracheal tube or through such devices as the Newton valve. It is also often difficult to assess the adequacy of ventilation when weaning a young child from ventilatory support. The Infanta respirometer provides useful information which may aid clinical judgement, and the results of this study show that its accuracy for tidal volumes between 15 and 200 ml is adequate for use in these clinical situations.

REFERENCES


