THE ACCURACY OF THE RESPIROMETER AND VENTIGRATOR

BY

J. F. NUNN AND T. I. EZI-ASHI

Departments of Anaesthetics, Royal College of Surgeons, and Postgraduate Medical School, University of London

SUMMARY

The respirometer under-reads at low flow rates and over-reads at high flow rates, but during anaesthesia, the respiratory waveform and the nature of the respired gas combine to minimize the low error which would otherwise result from hypoventilation. Over-reading is to be expected during hyperventilation of the anaesthetized patient. The error will always exaggerate a departure from normality.

The response of the ventigrator is proportional to the square of the gas flow rate. Consequently the sensitivity is poor at low flow rates and excessive at high flow rates and, furthermore, the signal is markedly influenced by the peak flow/minute volume ratio. The response of the ventigrator is directly proportional to the vapour density of the respired gases. Large corrections are, therefore, required during anaesthesia.

Routine monitoring of ventilation is not yet a part of the normal care of the anaesthetized patient. Nevertheless, the minute volume of ventilation is at least as important as the arterial blood pressure or the pulse rate, both of which are commonly measured during routine surgery. Anaesthetists have probably been deterred by the many existing techniques for the measurement of minute volume—none of which has yet found universal acceptance.

Apart from considerations of accuracy, a technique for the routine measurement of ventilation during anaesthesia should have the following features:

(1) It should be applicable to all anaesthetic gas circuits and should also be suitable for the patient breathing air without any apparatus. It follows that the only universally acceptable position for the measuring instrument is between the patient and the breathing apparatus (if present).

(2) If the measuring instrument is to be immediately adjacent to the patient, it must be able to measure tidal (to-and-fro) gas flow. This may be achieved either by the instrument being sensitive to flow in one direction only, or by the instrument responding in a similar manner to flow in both directions.

(3) If the patient is to breathe to-and-fro through the apparatus, its deadspace should be small (less than 30 ml) and it should not offer appreciable resistance to breathing.

(4) The apparatus should be compact, reasonably cheap and require no external source of power.

(5) It should not require calibration before use, and in simplicity of operation should compare favourably with the Riva Rocci method of measurement of arterial blood pressure.

Of the many available techniques for the measurement of minute volume, the most suitable for use during anaesthesia would appear to be the respirator anemometer (Wright, 1955—now marketed as the respirometer by British Oxygen Company Ltd.) and the ventigrator (Maloney, Silverman and Whittenberger, 1951) manufactured by the Ohio Chemical Company. This paper reports an attempt to determine whether these devices are sufficiently accurate for the clinical monitoring of ventilation in the anaesthetized patient.

The respirometer (fig. 1).

The Wright respirometer is a miniature air turbine with moving parts of very low inertia. The revolutions of the rotor are recorded by means of a gear train and dial of the type used in wrist watches. The instrument indicates directly on the dial the number of litres of gas...
which have passed between two successive readings. The respirometer responds to flow of gas in one direction only and it may, therefore, be used with tidal flow. In common with all inferential gas meters the response (indicated volume ÷ actual volume passed) is dependent upon flow rate, since slip occurs to a greater degree as the flow rate is decreased. At very low flow rates, the mechanism fails to move at all. At high flow rates the response tends towards a fixed value. The internal volume is 22 ml.

Four respirometers were used in these studies. All had been carefully handled since the maker's calibration and had not been subject to mechanical shock or gas flows in excess of 150 l./min.

For details of construction and maintenance, reference should be made to the instruction and maintenance manual published by the British Oxygen Co. Ltd. Medical Department.

*The ventigrator (fig. 2).*

As originally described, the ventigrator consists of a double-ended symmetrical venturi tube of throat diameter 7.5 mm, with a central pressure tap and two interconnected end taps. Gas flow in either direction causes a fall in pressure at the centre tap relative to the interconnected end taps, the pressure difference being a function of gas flow rate. During tidal flow a pressure differential is developed during both inspiration and expiration and the integrated mean pressure is related to the minute volume.

With normal minute volumes, the pressure difference is small and cannot be conveniently
measured with a water manometer or with an aneroid capsule manometer of the sensitivity customarily used for the measurement of airway pressure. The pressure difference can, however, be measured with a slant gauge, a two-liquid manometer or with a draught gauge (a sensitive aneroid used for measuring differences in ventilating systems). When damped, the pressure measuring device indicates the integrated mean pressure.

Two ventigrators were used in this study. One was constructed according to the recommendations of Maloney, Silverman and Whittenberger (1951) and was fitted with interconnected end taps. Internal volume was 17 ml. Pressure differences were measured with a Casella two-liquid manometer with a sensitivity of 1 cm per mm water gauge. The second ventigrator used in the study was the Minute Volume Meter manufactured by the Ohio Chemical Company. It differs from Maloney’s recommendations in having only one end tap, on the side of the ventigrator away from the patient. The signal is thus dependent upon the direction of the gas flow, as well as on the gas flow rate. The Ohio ventigrator is supplied with a draught gauge which is calibrated directly from 2 to 12 l./min minute volume. Different scales are provided for gases of varying vapour density. Internal volume is 12 ml.

**METHODS OF ASSESSMENT**

*Response to steady unidirectional gas flow.*

Air was drawn through the apparatus by a pump in the following order: respirometer or ventigrator; dry gas meter; rotameter (0–20 and 14–150 l./min); Douglas bag tap; pump.

The flow rate of air through the apparatus was adjusted by means of the Douglas bag tap to give the required flow rate as indicated by the rotameter. The reference measurement of gas flow was then made with the dry gas meter which had previously been calibrated for different gas flow rates by water displacement in the meter laboratory of the North Thames Gas Board. In fact the rotameter was always found to be within 2 per cent of the corrected dry gas meter reading. Gas flow was continued for several minutes and the time noted for the passage of an exact multiple of the cycling volume of the dry gas meter (2.5 litres). Errors due to temperature changes were avoided by drawing the gas through the apparatus rather than by blowing.

*Response to tidal flow.*

The respirometer and ventigrator were separately interposed between a reciprocating pump and a spirometer (fig. 3). The spirometer made a continuous record of the ventilation on a kymograph. Three types of pump were used. The first employed a Yorkshire coupling and had a waveform approximating closely to a sine wave. The second pump was a Starling Ideal pump whose non-symmetrical linkage resulted in a waveform which happened to bear a close resemblance to the spirogram of normal respiration (fig. 4). The third pump—employing a servo motor—was designed as a respiratory waveform simulator (Hill, Hook and Bell, 1960). Frequency, stroke volume and waveform were all adjustable, and in addition it was possible to introduce a delay which simulated the postexpiratory pause typically seen after heavy dosage of pethidine (fig. 4).

*Nitrous oxide.*

The effect of nitrous oxide on the respirometer and ventigrator was studied under conditions of tidal flow, using the apparatus shown in figure 3. The system was purged for 5 minutes with a flow of 10 l./min of nitrous oxide, with
THE ACCURACY OF THE RESPIROMETER AND VENTIGRATOR

FIG. 3
Apparatus for determining the response of ventigrator (shown here) or respirometer to tidal gas flow. The reference measurement of ventilation was made with the spirometer.

FIG. 4
Spirograms of the pumps used for simulation of patients as shown in figure 3.

the pump cycling and excess gas escaping below the spirometer bell. The effect of sulphur hexafluoride on the respirometer was studied in a similar manner.

Studies in anaesthetized patients.
Considerable experience was gained in the use of the respirometer and ventigrator under conditions of routine surgery. Direct comparison was made between the ventilation measured with the respirometer and with a continuous flow spirometer incorporated in a circle system (Nunn, 1956). The respirometer was reversed to measure both inspiratory and expiratory minute volumes. Since the continuous flow spirometer indicated the mean of the inspiratory and expiratory minute volumes, it was necessary to interrupt the fresh gas flow for a brief period to measure the difference between them.

RESULTS. I: THE RESPIROMETER
Steady unidirectional flow.
The respirometer measures flow in one direction only. It was found, however, to have an astonishing ability to respond to rapidly alternating gas flow. Thus the ripple produced by a diaphragm pump (oscillating at 100 cycles per second) would actuate the respirometer in the absence of a continuous flow of gas. Careful smoothing of gas
Response of the respirometer plotted against steady unidirectional flow rate (continuous line). The response is expressed as indicated flow divided by flow rate determined by dry gas meter. The broken line indicates the pressure drop across the respirometer.

Response of the respirometer to sinusoidal flow at different frequencies.

Response of the respirometer to tidal flow of different waveforms.

Response of the respirometer to varying lengths of postexpiratory pause.

Response of the respirometer to different gases. Tidal flow was generated with a Starling pump and expiratory flow was measured (peak flow/min volume = 2.2).

Signal (pressure drop measured as in figure 2) plotted against flow rate for the ventigrator. The resistance of the device approximated closely to the pressure drop/flow rate relationship shown. The broken line shows the resistance of a No. 10 Magill endotracheal tube for comparison.
flow is, therefore, required in studies of the response during continuous flow.

Of the several respirometers tested, a typical response is shown in figure 5. The response is expressed as flow indicated by respirometer divided by flow determined with the dry gas meter. This particular instrument was correct at 21.5 l./min and 6½ per cent fast at 80 l./min. It was 10 per cent slow at 9.5 l./min and ceased to respond at all at about 2.5 l./min. All four respirometers had responses within ±10 per cent within the range 10–60 l./min.

The broken line in figure 5 shows the pressure drop across the respirometer under conditions of steady unidirectional flow. This is only about one-fifth of the resistance to flow offered by a No. 10 Magill endotracheal tube.

Tidal flow.

With sinusoidal flow the response curve had the same general shape as with steady unidirectional flow (fig. 6). The response at any particular minute volume approximated to the response at a steady unidirectional flow equal to \( \pi \times \) the minute volume. Thus correct readings were obtained at a sinusoidal flow of 7 l./min (at 15 b.p.m.) and at a steady unidirectional flow rate of 21.5 l./min, the ratio 21.5/7 approximating closely to \( \pi \). With sinusoidal flow, peak flow rate equals \( \pi \times \) the minute volume; thus the respirometer appears to respond as though all gases passed at the peak flow rate. However, figure 6 shows a tendency for a higher response to occur at increased respiratory frequencies.

With non-sinusoidal tidal flow, the response curves were again of similar general shape. They were, however, displaced to the right or the left, according to the peak flow/minute volume ratio (fig. 7). With the Starling pump the inspiratory peak flow rate was greater and the expiratory peak flow less than with a sinusoidal flow of equal minute volume (fig. 4). The displacement of the response curves was such that approximately the same response was obtained with the same peak flow rate regardless of the waveform (table I). Similar changes were noted with a postexpiratory pause which was associated with a particularly high peak flow/minute volume ratio (fig. 8). Observations shown in figures 5, 6, 7 and 8 were obtained with the same respirometer.

Different gases.

With nitrous oxide, the response curve of the respirometer was moved above and to the left of the curve obtained with air (fig. 9). With sulphur hexafluoride the displacement was more marked still. Sulphur hexafluoride has a density of 5.1 compared with 1.53 for nitrous oxide and 1 for air. Over the range of minute volumes found during anaesthesia, the response given with nitrous oxide approximated to that found with air at a minute volume 3 l. greater.

Clinical studies.

The respirometer was easily adaptable to the gas circuits in common use. It was equally suitable attached to a mask or to an endotracheal adaptor. The tidal volume was immediately apparent, but measurement of the minute volume required the use of a watch. However, by using the zero-set and brake, determination of the minute volume required rather less effort than counting the pulse rate. Artificial ventilation presented no difficulty in the use of the respirometer.

Compared with a spirometer, the respirometer was found to indicate a tidal volume which, at a minute volume above 3.7 l., lay between the volume actually recorded at ambient temperature and pressure (saturated) and the same volume corrected to body temperature (table II).
This is in accord with the respirometer itself being between ambient and body temperature and suggests that, under the conditions of these observations, the minute volume was measured with an accuracy limited principally by the temperature of the respirometer.

During this study it was found that a spurious high reading (10 to 20 per cent fast) could be obtained by measuring the expiratory minute volume with the respirometer connected directly to a catheter mount. This was found to be due to the narrow bore of the catheter mount causing a jet of gas to impinge on a limited number of apertures in the respirometer—a condition which is known to cause a high reading. This effect could be eliminated either by inserting a length of wide bore tubing—1 inch (2.54 cm) I.D.—between the catheter mount and the respirometer or by inserting a baffle to break up the flow. A baffle has now been incorporated in the catheter mount adaptor supplied by British Oxygen Company.

RESULTS. II: THE VENTIGRATOR

Steady unidirectional flow.

The ventigrator gave a pressure difference which was proportional to the square of the gas flow rate. Figure 10 shows the signal obtained with the ventigrator constructed with interconnected end-taps. The resistance to flow was practically identical to the signal/flow rate relationship and was the same for flow in either direction. Figure 10 also shows the resistance of a No. 10 Magill endotracheal tube which is appreciably greater than that of the ventigrator.

The Ohio Chemical Company ventigrator is not symmetrical and the signal was found to be dependent on the direction of flow, being greater in the direction which would normally be used during inspiration (fig. 11). The signal in the expiratory direction was close to that shown in figure 10, and both were related to the square of the flow rate. The resistance of the Ohio Chemical Company ventigrator was less than the signal/flow rate relationship for both inspiration and expiration. The resistance to gas flow in both directions is shown as broken lines in figure 11.

![Pressure drop (signal) flow rate characteristics of the Ohio Chemical Company ventigrator](https://academic.oup.com/bja/article-abstract/34/7/422/284820/fig11)

Tidal flow.

With tidal flow the ventigrator was found to develop a pressure difference which was proportional to the square of the minute volume. Figure 12 shows the results obtained with inter-
Changes in frequency up to 35 b.p.m. had little effect upon response. Changes in waveform, however, increased the response as the peak flow/minute volume ratio increased (fig. 13, table III). The changes in response were considerable, the introduction of a 3-second postexpiratory pause increasing the signal by 63 per cent.

### Table III

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Peak flow/min volume ratio</th>
<th>Pressure difference at a minute volume of 5 l. (mm H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoidal</td>
<td>3.14</td>
<td>1.6</td>
</tr>
<tr>
<td>Sinusoidal with 1 sec postexpiratory delay</td>
<td>4.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Sinusoidal with 3 sec postexpiratory delay</td>
<td>7.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

### Different gases.

With nitrous oxide the ventigrator developed a signal which was approximately 50 per cent greater than with oxygen (table IV). This appeared reasonably constant and is roughly in accord with the ratio of their vapour densities to which the pressure drop in a venturi tube is known to be related.

### Table IV

<table>
<thead>
<tr>
<th>Minute volume (l.)</th>
<th>Pressure difference on O₂ (mm H₂O)</th>
<th>Pressure difference on N₂O (mm H₂O)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.3</td>
<td>3.5</td>
<td>1.52</td>
</tr>
<tr>
<td>10</td>
<td>6.0</td>
<td>9.0</td>
<td>1.50</td>
</tr>
<tr>
<td>15</td>
<td>13.8</td>
<td>20.5</td>
<td>1.49</td>
</tr>
</tbody>
</table>

### Clinical observations.

The ventigrator was remarkably simple to use although special adaptors were required with British gas circuits. After three or four breaths the pressure difference reading became steady and the minute volume could be directly read without delay. Changes in ventilation could be detected within a few breaths and it was easy to ventilate the patient artificially to a required minute volume. On the other hand, up to a minute volume of 2 l., the deflection could barely
be detected while even at 4 l. the sensitivity was still poor. It was particularly unfortunate that sensitivity was minimal at low minute volumes when the level might well be critical. Also, the apparatus was unduly sensitive at high minute volumes when small changes in the level were of little consequence. Furthermore a cough or forced expiration could easily force the manometer off scale (12 l./min).

An excessive pressure difference applied to a two-liquid manometer results in the interface between the liquids breaking down into a number of droplets. These take a long time to settle and the manometer is out of commission for a considerable time. The two-liquid manometer was not found to be practicable for use in the operating theatre. The draught gauge, on the other hand, continued to function satisfactorily, although it was never subjected to an excessive pressure difference.

**DISCUSSION**

*The respirometer.*

The present study confirms the over-reading of the respirometer at high minute volumes and the under-reading at low (Wright, 1958; Byles, 1960). The problem has been whether this would introduce a serious error into the monitoring of ventilation during routine anaesthesia. When breathing air with a sinusoidal waveform, the respirometer would normally read 10 per cent low, at a minute volume of about 3.4 l. Minute volumes of this order are certainly encountered in routine anaesthesia (Nunn, 1958), but two factors—waveform and the nature of the respired gas—combine to minimize, if not prevent, the error which might be expected.

Anaesthetized patients probably never breathe sinusoidally and, as respiration becomes more depressed, the breathing pattern usually departs more and more from a sine wave and often assumes a gasping form. Thus, as minute volume falls, the peak flow/minute volume ratio may be expected to rise and the peak flow rate, therefore, tends to be maintained at a fairly high level. This is fortunate as it has been shown that the response of the respirometer is largely dependent upon peak flow rate.

The relationship between waveform and low minute volumes was studied in 44 fast spirometer traces recorded during a previous study of spontaneous respiration under anaesthesia (Nunn, 1958). The spiromgrams were divided into three groups:

*Group A.* Postexpiratory pause less than 0.5 sec; spirogram resembling that of the Starling pump (fig. 4); inspiratory peak flow/min vol, 4 to 5; expiratory peak flow/min vol, 2 to 3.

*Group B.* Postexpiratory pause of 0.5 to 2 sec; spirogram resembling that of servo pump with 1-sec pause (fig. 4); peak flow/min vol, 4.5 to 6.

*Group C.* Postexpiratory pause of 2 to 4 sec; spirogram resembling that of servo pump with 3-sec pause (fig. 4); peak flow/min vol, 5.5 to 7.5.

The distribution of minute volumes in the three groups is shown in figure 14. In group A, the peak flow depends largely on whether inspiration or expiration is being monitored. During inspiratory monitoring the respirometer would not be expected to read 10 per cent slow until the minute volume fell below 2.3 l.—considerably below the lowest observed minute volume in this group. During expiratory monitoring, on the other hand, the reading would be more than 10 per cent slow below a minute volume of 5 l. In group B, there

![Figure 14](https://academic.oup.com/bja/article-abstract/34/7/422/284820/FIG_14)
was little difference between the inspiratory and expiratory peak flow rates and in this group the respirometer would not be expected to become 10 per cent slow until the minute volume fell below about 2 l. Only one instance of a minute volume below 2 l. was found in group B. In group C, there was again little difference between the inspiratory and expiratory peak flow rates and a 10 per cent error in the respirometer reading would only be expected below a minute volume of about 1.5 l. Thus during anaesthesia, low minute volumes tend to be accompanied by a change in peak flow/min volume ratio which does much to reduce the error which would otherwise be present.

The second factor tending to reduce errors in the direction of under-reading during anaesthesia is the almost invariable presence of either nitrous oxide or a heavy vapour. It has been shown above that this substantially reduces the minute volume at which a low error will appear.

It thus seems most unlikely that the respirometer will give an appreciably slow reading as a result of depressed breathing in routine clinical anaesthesia, particularly if the inspiratory rather than expiratory minute volume is measured. The observations reported in table II confirm that there is no significant error at least down to 3.7 l. If, however, the minute volume should fall to such low figures that an appreciable error is introduced, it is comforting to realize that the error will be in the direction of under-reading and that the underventilation will be highlighted. It would appear virtually impossible for dangerous underventilation to be concealed by a high error.

At the other end of the ventilation scale the question arises whether a high error may occur during hyperventilation. Minute volumes up to 20 l./min are relatively common during routine artificial ventilation of the anaesthetized patient (Nunn, 1958). Were sinusoidal waveform employed, peak flows of 63 l./min might be expected. However, during manual ventilation, the waveform is seldom sinusoidal and the pneumotachograph indicates that peak flows as high as 75 l./min are common. At these flow rates, respirometers usually read about 10 per cent high and the reading will probably be increased further still by the use of nitrous oxide. Nevertheless, it is unlikely that the error will be seriously outside the limits of ±10 per cent. Furthermore, the error during hyperventilation would tend to be high and stress the fact that the patient was being considerably overventilated.

It appears that the accuracy of the respirometer is adequate for clinical monitoring. Only during gross underventilation and moderate overventilation will its error exceed 10 per cent. Even then the error will be such as to exaggerate the departure from normality and many would regard this as desirable. The accuracy is greatest at a ventilation which is likely to keep the arterial $P_{CO_2}$ close to normal.

It is less easy to say whether the accuracy of the respirometer is adequate, as an alternative to the cumbersome spirometer, for the measurement of ventilation in research. This must depend upon the nature of the study. It would, for example, probably be adequate for measurement of the ventilatory response to drugs. On the other hand, it is unlikely that it would be suitable for studies of gaseous exchange or determination of deadspace.

Probably the most serious disadvantage of the respirometer is its liability to damage following a fall on to a hard floor. It is, however, doubtful whether any comparable measuring device would stand such a shock which amounts to a temporary deceleration of several hundred g. It is, regretfully, the compactness of the respirometer which results in its being dropped. Few workers have dropped the bulky dry gas meter, which would probably be no better able to withstand the shock. Following a fall, the most likely damage is to the mercury seal which separates the gear train from the moist air of the rotor compartment. If the mercury seal is lost, the rotor will still revolve as gas flows above about 6 l./min but the response is seriously reduced and the gear train may be damaged by moisture. The best test for loss of the seal is to walk slowly with the intake of the respirometer held forward. This should result in rotation of the rotor and the user should familiarize himself with this test.

The ventigrator.

The ventigrator is so simple to use that, at first sight, it seems to be the ideal respiration monitor for anaesthesia. However, it suffers from fundamental disadvantages which considerably reduce its value.
The most serious defect is the relationship of the signal to the square of the flow rate. This means that the sensitivity is worst at low minute volumes and best at high minute volumes. Not only is this quite the reverse of what is desirable but it also means that the response of the apparatus is unduly sensitive to changes in waveform, there being a seriously high error when the peak flow rate is high. Thus the introduction of a 3-second postexpiratory pause was found to increase the signal by 63 per cent when the minute volume was held constant.

Denser gases increase the response of the ventilator considerably more than with the respirometer—eight times as much in the case of nitrous oxide. The Ohio Chemical Company ventilator is equipped with different scales to make allowance for gases of different densities. However, not only is this an undesirable complication but, when nitrous oxide or cyclopropane is used in a closed circuit, it is often difficult to be certain of the composition of the inspired gas mixture (Woolmer, 1956). The ventilator itself is very robust, but a manometer of the required sensitivity would inevitably be delicate and certainly would not withstand dropping on the floor.

ACKNOWLEDGMENTS

This work was carried out while one of us (J.F.N.) was in receipt of a Leverhulme Research Fellowship. We are indebted to British Oxygen Company and to Dr. B. M. Wright for the loan of the respirometers and to Dr. F. S. Wood-Smith for the loan of the ventilator.

REFERENCES


SOMMAIRE

Le respiromètre indique des taux de flux trop bas lorsque le flux est faible et des taux de flux trop élevés lorsque le flux est fort, mais pendant l'anesthésie la forme ondulatoire de la respiration et la nature du gaz respiré interviennent ensemble pour minimiser la faible erreur qui résulterait autrement de l'hypoventilation. Des chiffres exagérés doivent être attendus pendant l'hyperventilation du patient anesthésié.

L'erreur exagérera toujours la déviation du taux normal.

La réaction du Ventigrator est proportionnelle au carré du taux du flux gazeux. Par conséquent la sensibilité sera faible au taux bas du flux et excessive lorsque ce taux sera élevé. D'autre part le signal est sensiblement influencé par le rapport entre flux maximal et volume par minute.

La réaction du Ventigrator est directement proportionnelle à la densité de vapeur des gaz respirés.

Pour cette raison des rectifications considérables seront nécessaires pendant l'anesthésie.

ZUSAMMENFASSUNG
