RESPIRATORY MECHANICS WITH CONSTANT FLOW INSPIRATION
A comparison of two measurement techniques

C. A. SHANKS, D. I. CAMPBELL AND H. TELFORD

SUMMARY
Respiratory compliance and resistance were measured during positive pressure ventilation in anaesthetized, paralysed dogs. Airway pressures measured during constant-flow inspiration allowed the calculation of pulmonary and chest-wall resistances, and static and non-static compliances. Contiguous studies of dynamic compliance and resistance allowed comparison of the two techniques, and the level of agreement was reasonable. Constant-flow inflation of the lungs allows a simple means of measuring respiratory mechanics, and should be valid for the observation of short-term changes in the apnoeic patient.

Of the techniques which are used to measure the compliances and resistances of the respiratory system, one "was found to be very suitable for use in apnoeic anaesthetized subjects. The apparatus was simple to use, readings could be made at frequent intervals and changes induced by various factors could be rapidly followed" (Don and Robson, 1965). This technique involves the recording of pressures in the airway during inflation of the lungs with a constant, known flow rate of gas. With accurate means of measuring and recording pressure changes, variations in the respiratory mechanics of the apnoeic patient may be observed, without complex apparatus.

We have examined values for the lung mechanics derived by the constant-flow inflation method and compared them with the results obtained by a classical technique for pulmonary dynamics (Mead and Whittenberger, 1953). The latter technique provides a pressure-volume loop for dynamic compliance and a pressure-flow loop for resistance; both of the loops describe each relationship during the whole respiratory cycle. Each loop is closed by electrical subtraction, thereby removing that element of pressure change which is unrelated to the loop being observed.

METHODS
Paired studies were made during constant flow inspiration (CFI) in 10 anaesthetized, paralysed greyhounds. A high pressure air source (400 kPa) was passed through a needle-valve flow controller to an endotracheal tube (fig. 1). A pneumatic on/off switch gave rapid manual control of the constant, 0.5-litre/s air flow. The flow was calibrated and adjusted before each reading by obtaining the correct pressure decrease across a known resistance. On the cessation of flow, the lungs were held in inspiration, 0.5–1.4 litre above FRC (after volume history). Flows could be continuous or intermittent.

Pressures were measured from air-filled catheters placed in the airway near the ends of the endotracheal tube. An oesophageal balloon (7 cm long and 2.5 cm in circumference) was positioned to obtain maximum subatmospheric pressures and secured in place. Intrapleural pressures were measured at the uppermost portion of the left pleural cavity after a small pneumothorax had been induced. Absolute and differential pressures were measured with Sanborn...
268B transducers. Flows were measured with a heated Fleisch pneumotachograph, and volumes were obtained by electrical subtraction (Mead and Whittenberger, 1953) during ventilation as outlined below. The output from the Sanborn 350 recorder was displayed on a Tektronix 5103N storage oscilloscope, from which the loops were photographed during X-Y operation.

The oscilloscope was converted to a time-based system, usually operated at 0.5 s per division, for pressure measurements with constant-flow inspiration. Timing the duration of the constant flow gave the inspired volume, and the appropriate pressures provided the compliances (fig. 2). Kinetic compliance was derived from the increasing pressure measured during inspiration. Inspiratory resistance was measured at FRC from the initial pressure step at the onset of the 0.5-litre/s CFI.

**Kinetic Compliance**

$$\text{Kinetic Compliance} = \frac{V_1}{P_3 - P_2} \text{ or } \frac{V_1}{P_4 - P_1}$$

**Static Compliance**

$$\text{Static Compliance} = \frac{V_1}{P_5 - P_1}$$

**Resistance**

$$\text{Resistance} = \frac{P_2 - P_1}{0.5} \text{ or } \frac{P_3 - P_4}{0.5}$$

Fig. 2. Static and kinetic compliances and respiratory resistances were calculated from the pressures recorded during constant-flow inspiration with anaesthetized, paralysed greyhounds. The volume ($V_T$) was derived from timing the 0.5-litre/s flow during the interval between $P_1$ and $P_5$.

Anaesthesia was induced with pentobarbitone, muscle relaxation being obtained with pancuronium. After endotracheal intubation, the dogs were placed in the left lateral position and ventilated at 20 b.p.m. with tidal volumes of 0.5–1 litre of air via a T-piece system. After matched control measurements, the respiratory mechanics were altered by the administration of histamine or tubocurarine i.v. or by inducing pulmonary oedema by oleic acid infusion. Strapping to the trunk was used to reduce compliance mechanically (Caro, Butler and DuBois, 1960). Resistances were constructed from tubing containing different lengths of sintered bronze, which were inserted into the airway at the endotracheal tube connections.

The dynamic compliance (Mead and Whittenberger, 1953) was plotted against the kinetic compliance (Don and Robson, 1965), and the results were analysed by linear regression. Total resistances were examined similarly.

All pressure values were those measured directly: in calculating lung compliance, the transpulmonary pressure was measured differentially by the 268B transducer. Although the oesophageal and intrapleural pressures were not comparable on all occasions (Agostoni, D'Angelo and Bonanni, 1970; Gillespie, Lai and Hyatt, 1973), it was required only that the two contiguous techniques used the same sites for pressure measurements. Similarly, it was assumed that the lung volumes did not change between the paired serial measurements with the two techniques, so that the return to atmospheric pressure in the airway at the end of expiration was to a similar FRC on the two occasions.

**RESULTS**

The apparatus gave a constant inspiratory flow (fig. 3), which produced a steady increase in airway pressure, the linearity of which was affected by changes in compliance or resistance, or both, and by the heartbeat. In turn, the heartbeat was affected by the positive pressure inspiration (fig. 4).

In some animals the pressure change with inflation was related almost entirely to compliance, and pulmonary resistance could be very low (fig. 3). Airway pressures measured at the mouth showed an added pressure step, as a result of the resistance of the endotracheal tube and its connections (fig. 4). When this was obviated by intratracheal measurements, simultaneous airway and intrapleural pressures showed more clearly the difference between total and chest-wall compliances (fig. 5a), and the proportion of the total natural resistance attributable to the "chest-wall". Resistance from tissues outside the lungs (thoracic cage, diaphragm and abdominal contents) could be shown as a small step in the pleural pressure, except where this was obscured by the
Fig. 3. Simultaneous pressure and flow measurements in a dog. The upper trace is differential pressure (tracheal minus oesophageal) which increased by 14 cm H₂O during flow, then remained steady during the 8 s recorded during the inspiratory hold. The lower trace shows the square wave of 0.5-litre/s constant flow operating for 1.7 s. When airways resistance is zero, the average kinetic lung compliance equals the static lung compliance, here 0.0607 litre/cm H₂O.

Fig. 4. Simultaneous mouth and oesophageal pressures recorded in a dog. During 1.3 s of constant flow, the resistance decreased from 9 to 5 cm H₂O/litre/s. The kinetic compliance was slightly higher than the static compliance. The oesophageal trace shows a diminution of the heartbeat with the application of positive pressure. The vertical bars are calibrations for 20 cm H₂O, that on the left being for the upper trace (airway pressure at the mouth).

Fig. 5. Tracheal and pleural pressures showing the effects of strapping applied to the chest wall. A. The tracheal trace (upper) showed very little resistance, and a subsequent differential trace confirmed that most of this was outside the lung. B. Following the application of strapping, static and kinetic total compliances were reduced by 50% and those for the chest wall by about 75%. The smaller step changes in tracheal pressure at the end of the 0.7-s inspiratory flow shows that resistance has decreased from its initial value, but the actual value cannot be determined. C. Four periods of flow subsequent to B indicate that airways resistance decreased with inflation. Simultaneous pleural pressures showed no change in the increased chest wall resistance. Calibrations are 20 cm H₂O pressure.
heartbeat. Figure 5 shows the changes following the application of strapping to the chest-wall. The effects of the i.v. injections were too unstable for reproducibility, and were not included in the statistical analysis. With this technique, resistance accounts for a pressure step at the commencement and cessation of the constant flow. As the lung volume increased from FRC, the resistance decreased (fig. 5a). The correlation between the volume increase from FRC and the change in resistance was examined by interrupting the constant flow inflation (fig. 5c).

Using pressures measured in the trachea of these adult greyhounds, the control values for resistance were very low. Although the various injections increased airways resistance, they carried a high mortality, thus the values shown in figure 6 were increases effected mechanically. This figure shows a reasonable correlation between the two techniques in the measurement of resistance, but with a tendency for the constant-flow system to give a high value.

The comparison between dynamic and kinetic compliances (fig. 7) includes the total and chest-wall compliance values obtained during matching studies which used the same method of pressure measurement. These two types of non-static compliance gave a relationship which was statistically highly significant. These could be as much as 20% higher than the corresponding values for static compliance.

**Fig. 6.** A comparison of resistances derived from pressure flow loops and those from constant-flow inspiration. These are all total resistances based on airway pressures alone. Changes related to chest strapping and the i.v. administration of chemicals were omitted from these calculations, but made little difference to the statistics. The graph shows 50 pairs matching the resistance from the pressure-flow loops (x) (mean = 14.3 cm H2O/litre/s) and the constant-flow inspiration (y) (mean = 16.6 cm H2O/litre/s). Regression analysis gave the equation $y = 1.01x + 2.2$, with a standard error of the estimate of 3.3 ($r = 0.98$).

**Fig. 7.** A comparison of the non-static compliances, including those altered mechanically by strapping, but not those following drug administration. The 58 pairs match dynamic compliance (x) (mean = 0.045 litre/cm H2O) and kinetic compliance (y) (mean = 0.046 litre/cm H2O). Regression analysis gave the equation $y = 0.98x + 0.002$, with a standard error of the estimate of 0.006 ($r = 0.96$).

**DISCUSSION**

Respiratory mechanics can be measured during positive pressure ventilation, using only a pressure recording system and a constant-flow inspiration (CFI). The CFI technique has been used infrequently during general anaesthesia (Don and Robson, 1965; Baker, Wilson and Hahn, 1974), despite its simplicity (Nunn, 1969). Don and Robson used it to measure flow resistance, static compliance and kinetic compliance, the latter term being introduced to distinguish an non-static compliance from the conventional dynamic compliance. They found also a decrease in pressure after CFI had ceased ("stress relaxation"). However, it would appear that the pressure decline of the duration and magnitude reported during the inspiratory hold would be explained most easily by the effect of gas leakage. Indeed, we used it as a check for such leaks.
Compliance

Static compliance. The ability to time precisely a known constant flow should give an accurate inflation volume, and this was confirmed in the laboratory. We are now studying adult patients by inflating 1 litre precisely by setting a fluidic timer to operate for 2 s of the 0.5-litre/s flow. Our CFI system is kept fully sealed, providing a steady pressure with the inspiration held; given the lung volumes and FRC, the static specific compliance is derived.

Non-static compliance. Don and Robson (1965) introduced the term “kinetic compliance” for the non-static compliance value derived during constant flow inflation. This differs from “dynamic compliance” (Mead and Whittenberger, 1953), which depends on the flow rate generated throughout the particular cyclical pattern of ventilation employed during the measurement. Dynamic compliance can be frequency-dependent (Brown et al., 1969; Woolcock et al., 1969), for example in lungs which have regions of differing time constants. Our studies gave a reasonable correlation between kinetic compliance and dynamic compliance. Presumably the effects of posture (Gillespie and Hyatt, 1972) or of chest strapping, in producing an inadequate volume history (Mead and Collier, 1959), were present in both the contiguous studies of the two techniques.

Resistance

Single continuous inflation. The onset of CFI gave a step increase in pressure, from which resistance was calculated. This value was that of the anaesthetized, paralysed animal at FRC, a volume which may be associated with airways closure (Kilburn, McDonald and Piccinni, 1960; Douglas, Chong and Findlayson, 1974). Airways resistance is higher during inspiration from near residual volume, decreasing with larger lung volumes (Briscoe and DuBois, 1958; Bouhuys and Jonson, 1967). Baker, Wilson and Hahn (1974) used the mean of the values at the beginning and end of CFI in their calculations, making the resistance figure more representative of the whole inspiration. However, gas redistribution could obscure the resistance component of a pressure change at the cessation of CFI, and for this reason we intend to use the flow onset values, as seen throughout inspiration with an interruption technique (fig. 5c).

Comparison of respiratory resistance. The resistance obtained by constant flow inflation was seldom lower than that derived by the technique of Mead and Whittenberger (1953) which averages resistance throughout the whole ventilatory cycle, and is thus influenced by the pattern of respiration. The resistance loop is closed electrically, using voltage subtraction to remove that pressure required to overcome elastic forces.

The tendency for CFI to over-estimate resistance should not preclude its clinical use. Comparison of short-term changes observed in the same patient should be valid when examining variations related to drug administration, particularly when these produce a reduction in respiratory resistance.

Interruption of continuous flow inflation. Since its introduction by von Neergaard and Wirz (1927), the interrupter technique for measurement of resistance has seen many variations. Jonson (1969) used it in spontaneously breathing subjects, in combination with a valve to regulate flow to a constant rate, and from this determined pulmonary elastic recoil and resistance. The interrupter technique tends to over-estimate airway resistance, and may be insensitive to induced changes (Mead and Whittenberger, 1954; Clements et al., 1959; Grimby et al., 1968; Frank, Mead and Whittenberger, 1971). Over-estimation may be related to the different breathing patterns used when techniques were compared, and can be reduced by a technique involving curvilinear extrapolation of the pressure trace back to the moment of interruption (Jackson, Milhorn and Norman, 1974). The single breath with CFI does not include factors related to respiratory frequency (Otis et al., 1956). Use of the interrupter technique during CFI could introduce alterations to resistance which are frequency-dependent (Grimby, et al., 1968; Cutillo et al., 1973).

Alveolar pressure change. Baker, Wilson and Hahn (1974) presented results to support their hypothesis that alveolar pressure responds to an instantaneous pressure change in a patient’s airway during artificial ventilation by an instantaneous step change. Their results from an electrical lung/thorax analogue had suggested that alveolar and pleural pressures might be expected to respond to a sudden flow-wave, as with CFI. Our studies confirmed this step change in oesophageal and pleural pressures. Even when the oscilloscope was operated at more rapid sweep rates, the intrapleural pressure step occurred simultaneously with that in the airway. The magnitude of this chest-wall resistance was increased slightly by the external application of strapping.
CONCLUSIONS

Respiratory mechanics can be studied during apnoea, using constant flow inflation (CFI). Given that the technical problems, such as those associated with gas-flow switching and leaks are eliminated, we would agree with Don and Robson (1965) regarding its ease and simplicity. CFI provides both static compliance and resistance, although the latter was found to have been over-estimated. The pressure trace also provides a non-static compliance and a curve related to gas redistribution, but these are complex to interpret.

ACKNOWLEDGEMENTS

We are most grateful to the Department of Surgery, University of Sydney, for the use of their laboratories and facilities. Dr A. J. Woolcock was most helpful with her revision of the manuscript.

REFERENCES


MECANIQUE RESPIRATOIRE AVEC INSPIRATION A DEBIT CONSTANT:

RESUME

La compliance et la résistance respiratoires ont été mesurées pendant la ventilation sous pression positive de chiens anesthésiés et paralysés. La pression des passages d’air mesurée pendant l’inspiration à débit constant a permis de calculer la résistance pulmonaire et celle des parois de la poitrine ainsi que les compliances statiques et non statiques. Des études apparentées sur la compliance et la résistance dynamiques ont permis de faire une comparaison des deux techniques et le degré de l’accord obtenu a été raisonnable. L’inflation des poumons à débit constant constitue un moyen simple de mesurer la mécanique respiratoire et devrait être valable pour l’observation des changements à court terme chez les patients apnéiques.
RESPIRATORY MECHANICS WITH CONSTANT FLOW INSPIRATION

RESPIRATORISCHE TÄTIGKEIT BEI BEATMUNG IN KONTINUIERLICHEM FLUSS:
Ein Vergleich Zweiwer Verschiedener Messmethoden

ZUSAMMENFASSUNG
Die respiratorische Dehnbarkeit und der respiratorische Widerstand wurden während positiver Druckbelüftung bei narkotisierten, paralysierten Hunden gemessen. Die in den Luftwegen während Beatmung in kontinuierlichem Druck gemessenen Drucke gestatteten die Berechnung der pulmonaren und Brustwand-Widerstände sowie der statischen und nicht-statischen Dehnbarkeiten. Ständige Untersuchungen von dynamischer Dehnbarkeit und dynamischem Widerstand gestatteten einen Vergleich der beiden Methoden, was ein vernünftiges Mass an Übereinstimmung ergab. Belüftung der Lunge in kontinuierlichem Fluss ist eine einfache Methode zur Messung der respiratorischen Vorgänge, und ist gültig für die Beobachtung kurzfristiger Veränderungen bei Apnoe-Patienten.

MECANICA RESPIRATORIA CON INSPIRACION DE FLUJO CONSTANTE:
Una Comparacion de dos Tecnicas de Medicion

SUMARIO
Se midieron la distensibilidad y resistencia respiratorias durante la ventilación de presión positiva en perros anestesiados, inmovilizados. Las presiones de la vía aérea medidas durante la inspiración de flujo constante permitieron calcular las resistencias pulmonar y de la pared torácica, y de las distensibilidades estática y no estática. Estudios ulteriores de la distensibilidad y resistencia dinámicas permitieron efectuar comparación de las dos técnicas, y el nivel de concordancia fue razonable. La insuflación a flujo constante de los pulmones proporciona un sencillo medio de medir la mecanica respiratoria, y debiera ser aplicable a la observacion de cambios de breve duración en el paciente apneico.