Static respiratory compliance in the newborn. I: A clinical and prognostic index for mechanically ventilated infants

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Abstract

Accurate measures of the severity of respiratory disease are important, both clinically and epidemiologically. The apparent prognostic value of static respiratory system compliance (Cr_s) on the first day and mean appropriate fractional inspired oxygen (F_{IO₂}) in the first 12 hours of life were compared in 48 infants who received mechanical ventilation in a regional neonatal unit. Their median (range) gestation was 30 (25–41) weeks and they were representative of all 140 newborn infants born to residents of a geographically defined area who received mechanical ventilation over a 30 month period. Using the best cut off value (≤ 0.6 ml/cm H₂O/m corrected for body length), static Cr_s predicted hospital death with 98% accuracy, 80% sensitivity, and 100% specificity. Using the best cut off value (> 0.60), mean F_{IO₂} in the first 12 hours predicted hospital death with 81% accuracy, 80% sensitivity, and 81% specificity. Static Cr_s appeared to be a more accurate measure of respiratory function and disease severity than mean F_{IO₂}, perhaps because static Cr_s is less dependent on ventilator management than routine indices based on blood gases. Static Cr_s now merits wider evaluation, both as an aid to routine clinical management and as a prognostic index in comparative studies. (Arch Dis Child 1994; 70: F11–F15)

Accurate assessment of disease severity is fundamental both for clinical management and in epidemiological studies. Clinically, any mismatch between the intensity of mechanical ventilation and the severity of respiratory disease – whether through over or under treatment – can have serious consequences. Individual assessment of respiratory disease severity demands considerable skill to interpret the degree of chest wall movement, the chest radiograph, and blood gas measurements. Unfortunately, blood gases can be misleading when impaired gas exchange is due to inappropriate ventilator settings leading to inadvertent positive end expiratory pressure¹ or obstruction of the pulmonary circulation.

Case reports

PATIENT A

A boy was delivered by caesarean section because of breech presentation in established

labour at 28 weeks' gestation. Ultrasonography from 22 weeks' gestation had suggested oligohydramnios. At birth he was resuscitated by endotracheal intubation with intermittent positive pressure ventilation and admitted to the neonatal unit where he received elective mechanical ventilation. The ventilator pressures and inspiratory:expiratory ratio were progressively increased (table 1). At 6 hours of age he was moribund, with extremely poor peripheral perfusion, a mean aortic blood pressure below 20 mm Hg, severe hypoxia, and respiratory acidosis. His chest wall expanded well with each ventilator inflation and his chest radiograph showed clear lung fields with over-expansion and no evidence of pulmonary hypoplasia. Severe pulmonary and peripheral underperfusion due to compression of the pulmonary vessels, heart, and aorta were diagnosed. The ventilator peak pressure and inspiratory:expiratory ratio were decreased and the ventilator rate was temporarily increased to reduce the arterial carbon dioxide tension (P_aCO₂). His arterial blood gases and blood pressure rapidly returned to normal. He continued to breathe air and was extubated successfully on the fifth day.

PATIENT B

A boy was delivered by emergency caesarean section after placental abruption in labour at

Table 1 Effects of inappropriate ventilator settings on gas exchange

Patient A*			
Age (hours)	0.5	6	9
Inspiratory time (sec)	0.5	0.8	0.25
Expiratory time (sec)	1.0	0.2	0.25
Inspiratory:expiratory ratio	1:2	4:1	1:1
Peak inspiratory pressure (cm H ₂ O)	20	32	18
End expiratory pressure (cm H ₂ O)	2	2	3
Mean airway pressure (cm H ₂ O)	6.3	24.5	9.0
F _{IO₂}	0.4	1.0	0.4
P _a O ₂ (kPa)	3.6	1.5	9.2
P _a CO ₂ (kPa)	9.1	10.5	5.3
pH	7.16	7.08	7.27
Patient B†			
Age (hours)	2	5.5	7
Inspiratory time (sec)	0.75	0.6	0.6
Expiratory time (sec)	0.45	0.4	1.4
Inspiratory:expiratory ratio	1.7:1	1.5:1	1.2:3
Peak inspiratory pressure (cm H ₂ O)	23	23	19
End expiratory pressure (cm H ₂ O)	5	4	4
Mean airway pressure (cm H ₂ O)	13.4	16.0	8.0
F _{IO₂}	0.45	0.3	0.21
P _a O ₂ (kPa)	8.5	10.1	11.5
P _a CO ₂ (kPa)	7.2	5.7	4.1
pH	7.28	7.35	7.47

*Patient A: dramatic illustration of the effect of inappropriately high ventilator pressure and inspiratory:expiratory ratio settings. The resulting compression of the pulmonary circulation, probably accompanied by inadvertent PEEP, caused severe hypoxia and respiratory acidosis, which resolved when the settings were reduced.

†Patient B: less dramatic example of a similar problem. (See case reports.)

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29 weeks' gestation. He was intubated at birth and received elective mechanical ventilation on admission to the neonatal unit. His chest radiograph at 3 hours of age showed diffuse reticulogranular densities and prominent hilar vessels, with no air bronchograms and no loss of the cardiac outline. He initially required a fractional inspired oxygen (FIO_2) of 0.4 (table 1). Measurement of respiratory function by a computerised passive expiratory flow technique² showed that respiratory compliance was relatively good (1.8 ml/cm $\text{H}_2\text{O}/\text{m}$) and the expiratory time constant was 0.19 seconds. This indicated that the lungs needed 0.57 seconds (that is three time constants) to achieve 95% emptying in passive expiration, that is, that the ventilator expiratory time was probably too short and the infant receiving inadvertent positive end expiratory pressure. The ventilator peak pressure and inspiratory:expiratory ratio were reduced and the ventilator expiratory time increased. The infant was successfully extubated at 12 hours of age, breathing air.

Epidemiologically, there has been long-standing interest in developing reliable methods to compare the outcome of respiratory care between different neonatal units. In particular, a seminal study by Avery *et al* has stimulated valuable insights and questions.³ This and similar studies remain difficult to interpret, however, because they lack measures of disease severity, without which there is no guarantee that like was compared with like. The best way to achieve comparability is by randomised studies, which tend to balance all prognostic variables (including disease severity) equally between groups. However, to compare the performance of neonatal units in this way would mean randomly transferring babies to receive intensive care in any of the neonatal units under study, which is not feasible. Comparisons of this kind must therefore use observational methods. These would be more reliable if accurate measures of initial disease severity were routinely recorded so that adjustments could be made for differences in casemix between the denominator (that is, treated) populations.

Provided oxygenation is adequately monitored, indices of oxygen requirement over the first 12 hours of life such as the mean or minimum and maximum appropriate FIO_2 or the mean arterial/alveolar oxygen ratio may provide routine measures of the initial severity of respiratory disease. In very low birthweight infants such indices seem at least as strongly associated with subsequent mortality as are traditional variables like birth weight, gestation, or hyaline membrane disease.^{4,5} Static respiratory system compliance (Cr_s) measured in the first 8 hours of life has also been strongly associated with subsequent mortality in mechanically ventilated infants.⁶ We therefore compared the potential clinical and epidemiological value of static Cr_s in the first day of life with mean FIO_2 in the first 12 hours of life in a representative group of infants receiving

mechanical ventilation in a regional neonatal unit.

Patients and methods

The study was conducted between April 1988 and September 1990 among infants admitted to the neonatal unit at Ninewells Hospital and Medical School. Infants were included if they had been born to residents of Tayside and were receiving mechanical ventilation by endotracheal tube, did not have an intercostal chest drain, and if one of the authors (RAW or WOT-M) was available to measure static Cr_s on the first day of life.

Static Cr_s was measured with infants supine employing a computerised passive expiratory flow technique.² This used a two way valve with a dead space of 4 ml to occlude airway flow and trap gas in the chest at or near maximum inflation for 0.2–0.5 seconds, which usually induced a Hering-Breuer reflex with relaxation of the respiratory muscles. The subsequent passive expiration was diverted via the other limb of the two way valve through a Fleisch 0 pneumotachograph (linear between 0 and 300 ml per sec) connected to a pressure transducer (Validyne MP 45±2 cm H_2O), which was sited outside the ventilator circuit and thus did not add to the dead space of the apparatus. The two way valve was cleaned thoroughly with alcohol between patients. The flow-volume characteristics of this expiratory breath were analysed using a system developed at the Children's Hospital, Toronto, by Professor A C Bryan, Dr M H Bryan, and Dr P N Le Souef.

Airway pressure was measured using a Validyne or Furness Controls transducer (0–10 kPa); flow and pressure signals were recorded from the pneumotachograph by an on line computer (IBM PC) at a sampling rate of 250 Hz per channel. The flow was digitally integrated and the resultant expiratory flow-volume curve displayed on the computer monitor. Flow-volume curves were only selected for analysis if the preceding airway pressure trace showed a flat plateau, indicating that no leak was occurring around the endotracheal tube. Respiratory function data were used only if the linear portion of the flow-volume curve accounted for two thirds or more of the expiration and the correlation coefficient of its slope exceeded 0.996.

In each study an average static Cr_s was obtained from flow-volume studies from between four and 12 passive expirations. Each measurement was preceded by endotracheal suction to avoid variations in airway resistance caused by secretions. Elsewhere we have reported that the mean (SD) within-study coefficient of variation in Cr_s between accepted breaths is 6.7 (3.5)%, the mean (SD) difference between the results of paired studies performed five minutes apart by the same observer is 0.2 (10.5)% and the mean (SD) difference between results obtained by two mutually blinded observers analysing the same data is 0.4 (7.4)%.⁷ The apparatus was calibrated weekly, because of the lack of drift on

Table 2 Characteristics of mechanically ventilated infants born to residents of Tayside in study period (data are expressed as median (range) except for hospital death and FIO_2)

	Static Crs measured on first day of life (n=48)	Static Crs not measured (n=92)
No of hospital deaths	5	11
Birth weight (g)	1270 (480–3500)	1440 (460–4100)
Gestation (weeks)	30 (25–41)	30 (24–39)
Length (cm)	39 (30–51)	
Age when Crs first measured (hours)	5.5 (0–24)	
Uncorrected Crs (ml/cm H_2O)	0.55 (0.2–2.0)	
Crs corrected for body length (ml/cm H_2O)	1.4 (0.6–4.2)	
Mean FIO_2 in first 12 hours	0.41 (0.21–0.79)	0.37 (0.21–0.75)

There were no significant differences between the two groups in hospital mortality, birth weight, gestation, or mean FIO_2 in first 12 hours.

day to day calibration. The pneumotachograph was calibrated using 100% oxygen. No attempt was made to correct for variations in gas composition. A single measurement of crown-heel length to within ± 1.5 cm was made at the time of the first Crs measurement using a tape measure.

FIO_2 was strictly controlled by continuously maintaining appropriate oxygenation, defined as arterial haemoglobin oxygen saturation between 90–94% using pulse oximeters (Nellcor) or transcutaneous oxygen tension between 6.7–10.5 kPa using transcutaneous oxygen electrodes (Simonsen and Weil). Mean FIO_2 was calculated as the average of all appropriate FIO_2 recordings on blood gas flow charts in the first 12 hours of life.

Table 3 Classification matrices for prognostic indices in relation to hospital death using best cut off points for each variable

	Predicted		Total	Significance
	Alive	Dead		
Crs corrected for length (ml/cm $\text{H}_2\text{O}/\text{m}$)	>0.6	≤0.6		
Observed:				
Lived	43	0	43	
Died	1	4	5	
Total	44	4	48	$\chi^2=27.8$; $p=0.0000014$
Gestation (weeks)	≥29	<28		
Observed:				
Lived	37	6	43	
Died	0	5	5	
Total	37	11	48	$\chi^2=14.2$; $p=0.00016$
Crs corrected for birth weight (ml/cm $\text{H}_2\text{O}/\text{kg}$)	>0.3	≤0.3		
Observed:				
Lived	36	7	43	
Died	1	4	5	
Total	37	11	48	$\chi^2=7.0$; $p=0.008$
Mean FIO_2 in first 12 hours	≤0.6	>0.6		
Observed:				
Lived	35	8	43	
Died	1	4	5	
Total	36	12	48	$\chi^2=6.0$; $p=0.014$
Hyaline membrane disease (HMD)	No HMD	HMD		
Observed:				
Lived	21	22	43	
Died	0	5	5	
Total	21	27	48	$\chi^2=2.58$; $p=0.10$

Distributions and classification matrices for birth weight, uncorrected Crs and Crs corrected for gestation were identical to those for Crs corrected for length, with cut off points for best discrimination for death of ≤ 750 g, ≤ 0.2 ml/cm H_2O , and <0.01 ml/cm $\text{H}_2\text{O}/\text{week}$.

Table 4 % Predictive power of variables

	Accuracy	Sensitivity	Specificity	Positive predictive value	Negative predictive value
Crs corrected for length	98 (47/48)	80 (4/5)	100 (43/43)	100 (4/4)	98 (43/44)
Gestation	88 (42/48)	100 (5/5)	86 (37/43)	45 (5/11)	100 (37/37)
Crs corrected for birth weight	83 (40/48)	80 (4/5)	84 (36/43)	36 (4/11)	97 (36/37)
Mean FIO_2 in first 12 hours	81 (39/48)	80 (4/5)	81 (35/43)	33 (4/12)	97 (35/36)

No predictive power is reported for hyaline membrane disease because the distributions of deaths and survivors were not statistically significantly different.

All infants were treated with Sechrist IV 100B ventilators (Anaheim, CA). Respiratory distress syndrome was diagnosed if an infant had a chest radiograph between 4–8 hours of age showing reticulogranular densities or a 'ground glass' appearance, or diffuse opacification with air bronchograms. No infant received exogenous surfactant. The study was approved by the Tayside committee on medical ethics.

STATISTICAL ANALYSIS

Group medians of non-normally distributed data were compared by Mann-Whitney U test and means of normally distributed data by Student's *t* test. Associations between hospital death and mean FIO_2 , Crs, birth weight, gestation, and hyaline membrane disease were tested on univariate analyses by χ^2 test with Yates's correction, selecting cut off values for each variable which yielded the best discrimination between survival and death. The proportions of deaths and survivors thus classified by each variable were calculated and compared using the following definitions: true positives=TP, true negatives=TN, false positives=FP, false negatives=FN; accuracy=(TP+TN)/total, sensitivity=TP/(TP+FN), specificity=TN/(TN+FP), positive predictive value=TP/(TP+FP), and negative predictive value=TN/(TN+FN).

Results

Characteristics of all 140 mechanically ventilated infants born to residents of Tayside during the study period are shown in table 2. The 48 infants studied did not differ in important prognostic characteristics from the 92 who were not, suggesting that the study group was a representative sample. Measurements of static Crs took up to 10–15 minutes and were well tolerated by the infant, with no evidence of destabilisation of oxygenation or – when it was continuously monitored – carbon dioxide tension. Of these 48 infants, 15 had no radiographic evidence of respiratory distress syndrome in the first 8 hours, and included babies ventilated electively or for asphyxia or congenital heart disease, with mean (SD) static Crs 1.9 (0.8) ml/cm $\text{H}_2\text{O}/\text{m}$; five had transient tachypnoea of the newborn with mean (SD) static Crs 1.6 (0.5) ml/cm $\text{H}_2\text{O}/\text{m}$, one had pneumonia with static Crs 1.2 ml/cm $\text{H}_2\text{O}/\text{m}$, and 27 had respiratory distress syndrome with static Crs 1.3 (0.5) ml/cm $\text{H}_2\text{O}/\text{m}$, which accounted for all five deaths. Tables 3 and 4 show classification matrices and the apparent predictive power of each variable using those cut off values that best discriminated between survival and death in Ninewells Hospital.

Discussion

This preliminary study shows that mean FIO_2 in the first 12 hours and static Crs measured on the first day were closely associated with subsequent mortality in mechanically ventilated

newborn infants, corroborating previous evidence of their apparent prognostic value.⁴⁻⁶ While both indices had considerable apparent predictive power, static Crs was the more accurate. These findings appear to be at variance with those of a recent investigation that used the same technique for measuring static Crs.⁸ However, in that report the population may have been unrepresentative because of a selection bias towards low risk infants, reflected in an unusually low mortality. As only 18 infants were mechanically ventilated in the study of Simbruner *et al*,⁶ to our knowledge ours is the largest yet reported of early static Crs in relation to mortality in a representative sample of newborn infants receiving mechanical ventilation. It was still relatively small, however, so some of the findings should be interpreted with caution.

Firstly, cut off values for each prognostic variable to distinguish between death and survival were not specified in advance, which increases the risk of a type 1 error. Although we could have prespecified ≤ 0.5 ml/cm H₂O as a cut off value for uncorrected static Crs because it best discriminated between death and survival in the study of Simbruner *et al*,⁶ we decided against it because that work was conducted a decade earlier. Indeed, the fact that a lower value of uncorrected static Crs of ≤ 0.2 ml/cm H₂O best discriminated between death and survival in our study is consistent with the fact that the prognosis for mechanically ventilated infants had improved. The best cut off point for predicting mortality may now be even lower, after the introduction of multiple dose surfactant treatment. It is important to stress that the likelihood that low static Crs and death are associated by chance alone in both studies is vanishingly small.

Secondly, static Crs was obtained over a longer period after birth than mean FIO₂. This may have biased the comparison of predictive power in favour of static Crs as – as in a horse race – predictions tend to be more successful the later they are made. Thirdly, both gestation and birth weight were closely related to death (table 3), so they may have confounded the associations between static Crs, mean FIO₂, and death. We have not attempted to analyse these associations independently by multiple regression because of the small sample size. However, we found previously that mean FIO₂ in the first 12 hours was an independent and more important predictor of death than gestation or birth weight.⁴ Furthermore, Simbruner *et al* found that in infants with respiratory symptoms static Crs was not correlated with gestation at all.⁶

It is important to correct measurements of Crs for body size. Otherwise in small infants an apparent association between low, uncorrected Crs and death might reflect the small size of the lungs rather than disease severity. Crs has been corrected for functional residual capacity (FRC), weight, length, and length cubed but none is ideal. In healthy subjects Crs is often expressed as specific lung compliance by correcting for FRC, but FRC cannot always be measured and may itself be reduced in surfac-

tant deficiency. Should static Crs be corrected for weight or for length? Weight may fluctuate substantially in the first weeks of life, while length is hard to measure accurately in babies. Neonatologists have tended to correct Crs measurements for birth weight, while paediatricians, respiratory physicians, and physiologists have used length (or height). Studies in normal infants suggest that static Crs is linearly related with weight but that its relationship with length is curvilinear.⁹⁻¹² Neither line passes through the origin: static Crs plotted against weight intercepts the Crs axis while static Crs plotted against length intercepts the length axis.¹⁰⁻¹² Thus correction for length could slightly overestimate the disease severity of smaller infants and underestimate the disease severity of larger infants. Correction for weight could have the opposite effect, perhaps predisposing larger infants with less severe lung disease to be treated with surfactant unnecessarily.⁷ As length was estimated to within ± 1.5 cm, errors in its measurement in a baby 40 cm long with static Crs of 1.0 ml/cm H₂O could lead to variations of ± 0.1 cm H₂O/m. Despite this, correction of static Crs for length has proved a marginally better discriminator of death (tables 3 and 4) and lung immaturity¹³ than static Crs corrected for birthweight. We were unable to determine a normal range for static Crs as few babies with normal lungs were intubated. In healthy preterm babies the normal range for static Crs is approximately 0.8–4.0 ml/cm H₂O or 0.5–1.7 ml/cm H₂O/kg.⁹⁻¹⁰ However, these data were obtained using a facemask and may not be completely comparable with data in intubated babies. More data on static Crs values in normal and diseased infants of all ages and sizes are needed.

Our findings have clear clinical implications. Firstly, while blood gas measurements are an important clinical index of disease severity, they can be misleading if, for example, the infant is overtreated with inappropriate ventilator settings,¹ as illustrated in the case reports. The problem of overtreatment could become more common as antenatal and postnatal steroids¹⁴⁻¹⁵ and exogenous surfactant treatment reduce the severity and duration of respiratory disease. Is static Crs a better clinical index than dynamic compliance? If excessive peak inflation pressure is used both static and dynamic compliance may be underestimated because the lungs are operating on a flatter portion of the pressure volume curve. In other circumstances, however, static Crs may be less liable to distortion by ventilator management.¹⁶ For dynamic compliance, tidal volume is constrained by the ventilator settings between the peak and positive end expiratory pressures (PEEP). The lung may thus remain overdistended during expiration because of continuing PEEP, leading to reduced tidal volume and underestimation of true lung compliance. In contrast, during measurement of static Crs in passive expiration the lung deflates to atmospheric pressure and tends to return to its natural functional residual capacity. Static Crs may thus provide a robust,

Table 5 Performance of various prognostic indices in predicting death in hospital

	No	Sensitivity (%)	Specificity (%)
Neonatal Crs ≤ 0.5 ml/cm H ₂ O (Vienna Children's Hospital)*	82	89	99
VLBW infant predictive model†	262	81	75
Neonatal Crs ≤ 0.6 ml/cm H ₂ O/m $\ddagger$ (Ninewells Hospital)*	48	80	100
Physiology stability index ¹⁸	2400	67	99
NIH VLBW infant model ²³	387	54	89
APACHE II ¹⁷	5030	47	95

VLBW=very low birthweight.

*Except for those based on neonatal Crs, each index was generated in a 'training sample' of patients and validated in a separate 'test sample' of patients; 18 of the 82 patients in Vienna were mechanically ventilated.⁶

†In this study the 'training' and 'test' samples excluded infants who were admitted to the intensive care units but did not receive assisted ventilation. Because their risk of death is low, had such infants been included the specificity of the model would have increased, with little change in its sensitivity.

‡Equivalent to Crs ≤ 0.2 ml/cm H₂O uncorrected for body length.

independent measure of respiratory function¹³ and disease severity to supplement blood gas measurements and perhaps improve clinical management (patient B).

Secondly, early and accurate prognostic indices could enhance clinical audit by focusing attention on the management of infants who die (or survive) unexpectedly. They could also provide clinical staff and parents with clearer prognoses soon after admission. However, it would be unwise to withdraw intensive care in any individual simply because the calculated risk of death is high, as the calculations are derived from previous cohorts of infants. Prognosis in neonatal intensive care is changing rapidly and healthy survival against the odds is always possible.

Our findings may also have implications for perinatal epidemiology and health service research. Predictive models or scoring systems based on early severity of disease are being developed in several disciplines¹⁷⁻²⁰ to allow better prognostication and more reliable comparisons of clinical outcome adjusted for casemix. Table 5 compares the predictive power of some of these systems with that of static Crs and early oxygenation in this study and suggests that such prognostic systems may be robust and widely applicable.

Reliable routine indices of initial disease severity could also improve the interpretation of many comparative studies. The randomised controlled trial of high frequency oscillatory ventilation versus conventional ventilation reported by the HIFI group showed no overall difference in chronic lung disease between the two groups.²¹ Nevertheless it is still possible that high frequency oscillation prevents chronic lung disease in subjects with respiratory failure as severe as that induced in the original animal models.²² This hypothesis should perhaps be tested by reanalysing the unpublished study data to compare outcomes in the stratum of infants with most severe early disease.

In summary, accurate measures of respiratory disease severity have an important part to play in clinical practice and comparative studies. Static Crs appears to be a valuable index of the severity and prognosis of

respiratory disease and – particularly in clinical management – might usefully complement more routine indices based on blood gases. Static Crs now merits wider evaluation.

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