The impact of shunt size on lung function in infants with univentricular heart physiology*

Iren L. Matthews, MD, MRCP; Per G. Bjørnstad, MD, PhD; Runa H. Kaldestad, RN; Lise Heiberg, MD; Erik Thaulow, MD, PhD; Morten Grønn, MD, PhD

Objectives: **To assess the relationship that shunt size, blood gases, and radiologic findings has on respiratory function in infants with univentricular heart physiology.**

Setting: **Cardiac catheter laboratory at Rikshospitalet University Hospital, Norway.**

Patients: **Fifteen infants with univentricular heart physiology admitted for cardiac catheterization.**

Measurements: **Lung function was measured by a fixed-orifice differential pressure flow sensor and mainstream volumetric capnography in 15 infants with univentricular heart arrangements during routine invasive assessment before the bidirectional cavopulmonary connection. Blood gases were measured from the indwelling catheters. Chest radiographs were assessed for heart size and pulmonary vasculature. Shunt size was assessed angiographically.**

Main Results: **Respiratory compliance was reduced in patients with a large surgical systemic-pulmonary arterial shunt ($r = -0.67$, $r^2 = 0.45$, $p = 0.03$). Respiratory resistance was higher with increased heart size ($r = 0.72$, $r^2 = 0.52$, $p = 0.004$). There was no association between arterial and end-tidal CO_2 values. The arterial to end-tidal CO_2 difference had an inverse relationship with the pulmonary to systemic shunt ratio ($r = -0.38$, $r^2 = 0.14$, $p = 0.015$).**

Conclusion: **A large surgical shunt size is related to stiffer lungs and a large heart is associated with a higher respiratory resistance. During mechanical ventilation of patients with univentricular heart physiology the end-tidal CO_2 may be an unreliable substitute for arterial CO_2 before the bidirectional cavopulmonary connection. We found a relationship between a decreased pulmonary to systemic shunt ratio and an increased arterial to end-tidal CO_2 difference. This may indicate that a reason for the unreliability of end-tidal CO_2 is an impaired gas exchange partially due to pulmonary hypoperfusion. (Pediatr Crit Care Med 2009; 10:60–65)**

KEY WORDS: congenital heart defects; thoracic surgery; cardiac catheterization; angiography; respiratory mechanics; capnography

Infants with congenital heart defects often have respiratory symptoms and disturbed lung function because of impaired pulmonary mechanics and impaired gas exchange. Knowledge of lung function parameters can aid the management of artificial respiratory support. This is especially important in infants with complex congenital heart defects such as univentricular heart physiology who undergo advanced heart surgery and often experience a turbulent postoperative course.

During anesthesia, modern ventilators provide lung function variables measuring gas exchange such as end-tidal CO_2 and capnography and pulmonary mechanics such as respiratory system compliance (C_{rs}) and respiratory system resistance (R_{rs}). However, these variables may be influenced by the univentricular heart physiology. The measurement of end-tidal CO_2 is routinely performed during anesthesia because it reflects arterial CO_2 (1, 2) and can, therefore, be used to guide mechanical ventilation, although in patients with cyanotic congenital heart disease this relationship has been found to be less reliable (3). The gas exchange and thereby the elimination of CO_2 will be affected by the venous blood bypassing the lungs through the shunt and by the reduced pulmonary perfusion. C_{rs} (which is the change in volume divided by the change in pressure) and R_{rs} (which is the change in pressure divided by the change in air flow) have been found to be influenced by pulmonary blood flow (4–6).

Infants with univentricular heart physiology usually need a surgical shunt in the neonatal period. The surgical shunt size needs to be large enough to provide sufficient blood for adequate oxygenation and at the same time not overloading the pulmonary circulation. As the infant grows the relative shunt size decreases and consequently their oxygen saturation will decrease. Therefore, after a few months a cardiac catheterization is normally performed to assess the suitability for the creation of a bidirectional cavopulmonary connection so that the superior caval vein feeds the pulmonary circulation. The study was planned to clarify factors of importance for the handling of mechanical ventilation in regards to gas exchange and lung mechanics in patients with univentricular heart physiology. We, therefore, aimed to measure lung function variables that are readily available during anesthesia and to assess their relationship with the size of the shunt, blood gases, and radiologic findings.

***See also p. 139.**

From the Department of Pediatrics (ILM, RHK), Pediatric Pulmonology and Allergology Unit, Rikshospitalet University Hospital, Oslo, Norway; Pediatric research Institute (ILM), Rikshospitalet University Hospital, Oslo, Norway; Department of Pediatrics (PGB, ET), Pediatric Cardiology Unit, Rikshospitalet University Hospital, Oslo, Norway; Radiology Department (LH), Rikshospitalet University Hospital, Oslo, Norway; and Department of Pediatrics (MG), Neonatology Unit, Rikshospitalet University Hospital, Oslo, Norway.

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The work was carried out at the Department of Pediatrics, Rikshospitalet University Hospital, Oslo, Norway.

Address requests for reprints to: Iren Lindbak Matthews, MD, MRCP, Pediatric Pulmonology and Allergology Unit, Department of Pediatrics, Rikshospitalet University Hospital, Sognsvannsveien 20, 0027 Oslo, Norway. E-mail: iren.matthews@rikshospitalet.no or n.i.l.matthews@medisin.uio.no

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MATERIALS AND METHODS

Patients. Children taking part in a longitudinal study on lung function in patients with univentricular heart arrangements were eligible if they were going for an elective cardiac catheterization before a bidirectional cavopulmonary connection between August 2002 and October 2006. The criterion for inclusion into the longitudinal study was that the infant would require a total cavopulmonary connection. Exclusion criteria were birth weight <2.5 kg, gestational age <36 wks, and other noncardiac serious malformations or syndromes. Nineteen patients were eligible. Four patients were missed and 15 patients (79%) were included. The study was approved by the Regional Committee for Medical Research Ethics and written informed consent was obtained from the parents.

Anesthesia and Cardiac Catheterization. Anesthesia was induced with a combination of thiopental and fentanyl. The children received cisatracurium for muscle relaxation. Anesthesia was maintained with isoflurane and bolus doses of fentanyl and thiopental. Muscle relaxation was maintained with bolus doses of cisatracurium. The children were ventilated with a Siemens Servo 900c volume controlled ventilator. Uncuffed tracheal tubes were used. The ventilator setting and oxygen level were selected by the anesthetist and changed as required by the clinical status but aiming for a tidal volume of about 10 mL/kg.

The elective cardiac catheterization was performed according to routine practice. All data were obtained without knowledge of the lung function findings. The blood pressures in the heart and the great vessels were measured by intra-arterial and intravenous catheters. Blood gases were measured in blood samples from the indwelling catheters. The pulmonary to systemic shunt ratio (Q_p/Q_s) was calculated by using oxygen saturations [Q_p/Q_s = (arterial oxygen saturation−mixed venous oxygen saturation)/(pulmonary venous oxygen saturation−pulmonary arterial oxygen saturation].

Shunt Size. The size of the shunt was evaluated by both the reported diameter of the surgical Goretex graft placed at operation and by the measured shunt diameter at angiography. The normalized shunt size was defined as the cross-sectional area of the shunt in millimeter square divided by the patient's current weight in kilogram [i.e., (diameter in mm/2)^2 × 3.14/kg]. The narrowest diameter of the ventricle-pulmonary connection in the patients with a naturally occurring shunt was assessed by angiography. The normalized size was defined as the cross-sectional area of the narrowest point in millimeter square using the same formula as above.

The length of the right ventricle-pulmonary artery conduit was measured by angiograms. The length was determined from a sagittal view of the conduit measured from the outer wall of the right ventricle to the insertion of the shunt into the pulmonary artery.

Lung Function Measurements. The lung function measurements were performed with the CO_2SMO Plus respiratory profile monitor that measured flow and pressure at the airway opening by a fixed-orifice differential pressure flow sensor inserted between the tracheal tube and the ventilator circuit. Volumetric capnography was performed by a mainstream infrared absorption technique sensor attached to the flow sensor. Variable values for each breath were stored in a connected computer by running Analysis Plus, a complementary software program (Novametrix Medical Systems, Wallingford, CT). The lung function variables were calculated from a mean of 30 ventilatory cycles, 15 mins after the start of respiratory support when ventilation was regular and the patient had no respiratory effort.

The tidal volumes were calculated by digital integration of flow. Dynamic total respiratory system compliance and resistance were computed by CO_2SMO Plus using the least squares regression method. The volume of CO_2 elimination per minute was calculated by the volume of CO_2 per breath times the respiratory rate. The physiologic dead space to tidal volume ratio was calculated using the CO_2SMO Plus respiratory profile monitor and the accompanying software by entering an arterial CO_2 value obtained during the cardiac catheterization. The software is based on automatic recognition of the different phases of the expired CO_2 to expired volume plot. Physiologic dead space is alveolar dead space plus airway dead space. Alveolar dead space is the alveolar volume not taking part in ventilation. Tracheal tube leakage was calculated as the difference between inspired and expired tidal volume divided by tidal volume times 100. A leakage of >10% may affect the reliability of respiratory mechanics (7) and a leakage of >10% was used as exclusion criteria for respiratory resistance and compliance.

Radiologic Examination. The chest radiographs were examined separately by a pediatric radiologist and a cardiologist unaware of the lung function findings. When the assessment varied a second radiologist assessed the chest radiographs. The two radiologists then reviewed the chest radiographs together and decided the final scoring value and their decision was chosen for the analysis. The radiologist and the cardiologist assessed the chest radiographs twice to assess the intraobserver agreement. The interobserver agreement was assessed between the pediatric radiologist and the pediatric cardiologist. The scoring system for the chest radiograph was based on our clinical practice of reporting chest radiographs in infants with congenital heart disease. The chest radiographs were assessed for pulmonary vasculature and heart size. The pulmonary vasculature was graded 1 to 4 (1= reduced vasculature, 2 = normal vasculature, 3 = slightly increased vasculature, 4 = increased vasculature). The heart size was graded 1–4 (1 = normal, 2 = slightly enlarged, 3 = enlarged, 4 = much enlarged). The rate of inflation was categorized as normal or hyperinflated. The sizes of the pulmonary arteries were measured from cineangiograms. The Nakata index (8) that is the cross-sectional area of the left pulmonary artery plus the cross-sectional area of the right pulmonary artery divided by the body surface area [i.e., (diameter in mm/2)^2 × 3.14 + (diameter in mm/2)^2 × 3.14/body surface area in m^2] was calculated. The surgical shunt size was also assessed by angiograms (see under shunt size).

Outcome Data. We noted the length of hospital stay at our institution and the length of respiratory support after the bidirectional cavopulmonary connection and examined the association with lung function data.

Statistical Analysis. Normality was assessed by QQ plots and histograms. Results are expressed as mean and SD. Pearson linear correlation analyses were performed between measures of lung function as one parameter and cardiac catheterization data, or radiologic findings or outcome measures as the other. Differences in lung function between patients who were found to have radiologic signs of hyperinflation and those whose lungs were normally inflated were done with the independent samples Student's t test. A probability of $p < 0.05$ was considered significant. The inter- and intraobserver agreement was assessed by kappa statistics. The computer program SPSS.14.0 (SPSS, Inc, Chicago, IL) was used for all analysis.

RESULTS

Clinical Data. There were eight patients with hypoplastic left heart syndrome, two with a double inlet single left ventricle, two with a single inlet single ventricle (mitral and tricuspid atresia, respectively), two with a straddling tricuspid valve (one patient with superior inferior ventricles with a large ventricular septal defect and one patient with ventricular inversion with hypoplastic anatomical right ventricle), and one with single ventricle with tricuspid hypoplasia. There were nine boys and six girls. Twelve patients had a surgical shunt procedure in the neonatal period, of which three had a central shunt and nine had a right ventricle-pulmonary artery conduit. The remaining three had a heart defect with a naturally occurring adequate shunt. Clinical data are shown in Table 1.

Cardiac Catheterization Data and Lung Function. The mean tracheal tube leakage was 1.9%, SD = 4.5. One patient had a tube leakage of >10% and the pulmonary mechanics were therefore excluded for this patient. In one patient, the value for the right atrial pressure was missing.

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Table 1. Clinical data

Clinical Data	Numbers	Mean	Standard Deviation	Ranges
Age at study (wks)	15	23.5	9.2	12.3–43
Weight at study (kg)	15	6.8	1.4	4.9–9.6
Length at study (cm)	15	65.1	4.4	58.5–73
Age at first operation (days)	12	8	5.1	5–19
Oxygen saturation at a mean of 4 days after birth (%)	15	91	6	72–99
Oxygen saturation at discharge after the first operation (%)	12	80	5.6	70–89
Weight at discharge after the first operation (kg)	12	3.9	0.7	2.9–5.4
Length of hospital stay after the bidirectional cavopulmonary connection (days)	15	6	1.5	4–9
Length of respiratory support after the bidirectional cavopulmonary connection (hrs)	12	3.1	1.5	1–6

Table 2. Respiratory data

Lung Function Measurements	Mean	Standard Deviation
Mean airway pressure (cm H_2O)	5.4	1.9
Respiratory rate per minute	21.6	4.4
Respiratory system compliance (mL/cm H_2O/kg)	0.87	0.17
Respiratory system resistance (cm H_2O/L/sec)	45.7	11.7
Volume of CO_2 elimination per kilogram (mL/min/kg)	4.8	0.9
Physiologic dead space/tidal volume ratio	0.49	0.09
End-tidal CO_2 Torr (kPa)	34 (4.5)	5 (0.7)

Table 3. Hemodynamic and angiographic parameters from cardiac catheterization

Measurements	Mean	Standard Deviation
Mean right atrial pressure (mm Hg)	5.8	1.5
Arterial oxygen saturation (%)	70.1	9.2
Central venous oxygen saturation (%)	51.8	6.3
Arterio-venous oxygen saturation difference	18.1	7.2
Pulmonary blood flow/systemic shunt ratio	0.77	0.36
Nakata index (mm^2/m^2)	243	108
Arterial pO_2 Torr (kPa)	51 (6.8)	16 (2.1)
Arterial pCO_2 (kPa)	38 (5.1)	6 (0.8)

All variables were normally distributed. The lung function parameters are shown in Table 2 and cardiac catheterization data in Table 3. There was an inverse relationship between the right atrial mean pressure and the C_{rs}/kg, ($r = -0.61$, $r^2 = 0.37$, $p = 0.03$, n = 14), and a positive correlation between R_{rs}, ($r = 0.55$, $r^2 = 0.30$, $p = 0.049$, n = 14). This means that patients with higher right atrial pressure have stiffer lungs and higher respiratory resistance.

The pulmonary to systemic shunt ratio had an inverse relationship with the arterial CO_2 level ($r = -0.67$, $r^2 = 0.45$, $p = 0.006$, n = 15), meaning that the larger the pulmonary to systemic shunt ratio the lower the arterial CO_2. The arterial and the end-tidal CO_2 level did not correlate ($p = 0.32$) see Figure 1. The arterial to end-tidal CO_2 difference had an inverse relationship with the pulmonary to systemic shunt ratio ($r = -0.38$, $r^2 = 0.14$, $p = 0.015$, n = 15). This means that the lower the pulmonary to systemic shunt ratio the bigger the difference between the arterial and the end-tidal CO_2. The pulmonary to systemic shunt ratio did not correlate with lung mechanics or with end-tidal CO_2 ($p = 1.0$).

Shunt Size and Lung Function. The mean normalized shunt size assessed as the reported size of the inserted Goretex graft was 3.33 mm^2/kg, SD = 1.41 (n = 12). This had an inverse relationship with the C_{rs}/kg ($r = -0.60$, $r^2 = 0.36$, $p = 0.05$, n = 11) and positive relationship with R_{rs}, ($r = 0.61$, $r^2 = 0.37$, $p = 0.047$, n = 11). The mean normalized shunt size assessed by angiography was 2.38 mm^2/kg, SD 1.39, n = 15) and it had an inverse relationship with C_{rs}/kg, ($r = -0.67$, $r^2 = 0.45$, $p = 0.03$, n = 11) see Figure 2. This means that patients with a larger shunt size measured both by the size of the inserted graft in the neonatal period and measured angiographically by the current size of the shunt had stiffer lungs.

The narrowest diameter of the ventricle-pulmonary connection in the three patients with a naturally occurring shunt was assessed by angiograms. One patient had a diameter of 7 mm and two had a diameter of 5 mm. The normalized size of this restriction to pulmonary blood flow was calculated in the same way as the size of the surgical shunt. These measurements were included in the assessment of the relationship between the size of the shunt and lung function variables. There was an inverse relationship between the normalized size of the shunt (both surgical and naturally occurring) and C_{rs}/kg ($r = -0.60$, $r^2 = 0.36$, $p = 0.03$, n = 14).

The mean length of the right ventricle-pulmonary artery conduit was 39 mm, SD 7, range 25–46 mm. There was no relationship between the length of the shunt and lung function variables.

Chest Radiograph and Lung Function. The interobserver agreement had a kappa value of 0.56 for the assessment of heart size, 0.12 for the assessment of pulmonary vasculature markings, and 0.6 for the assessment of hyperinflation. The intraobserver agreement assessed by the pediatric radiologist had a kappa value of 0.64 for the heart size, 0.31 for the pulmonary vasculature, and 0.88 for hyperinflation. The kappa values for the pediatric cardiologists were 0.35 for the heart size, 0.22 for the vasculature, and 0.85 for the hyperinflation. Using the classifications system by Landis and Koch (9) a Kappa value of <0.00 indicates a poor strength of agreement, 0.00–0.20 is slight, 0.21–0.40 is fair, 0.41–0.60 is moderate, 0.61–0.80 is substantial, and 0.81–1.00 is almost perfect. This means that the interobserver agreement was moderate for the heart size and hyperinflation and slight for the vasculature. The intraobserver agreement varied from fair to substantial accuracy for the heart size, from slight to fair for the vasculature and almost perfect for hyperinflation. The mean grading of pulmonary vasculature on the chest radiograph was 2.1, SD = 0.9, n = 15. There was no correlation with lung function. The mean grading of cardiac size was 2.4, SD = 0.83, n = 15. Cardiac size grading was inversely related with C_{rs}/kg ($r = -0.58$, $r^2 = 0.34$, $p = 0.03$, n = 11) and positively

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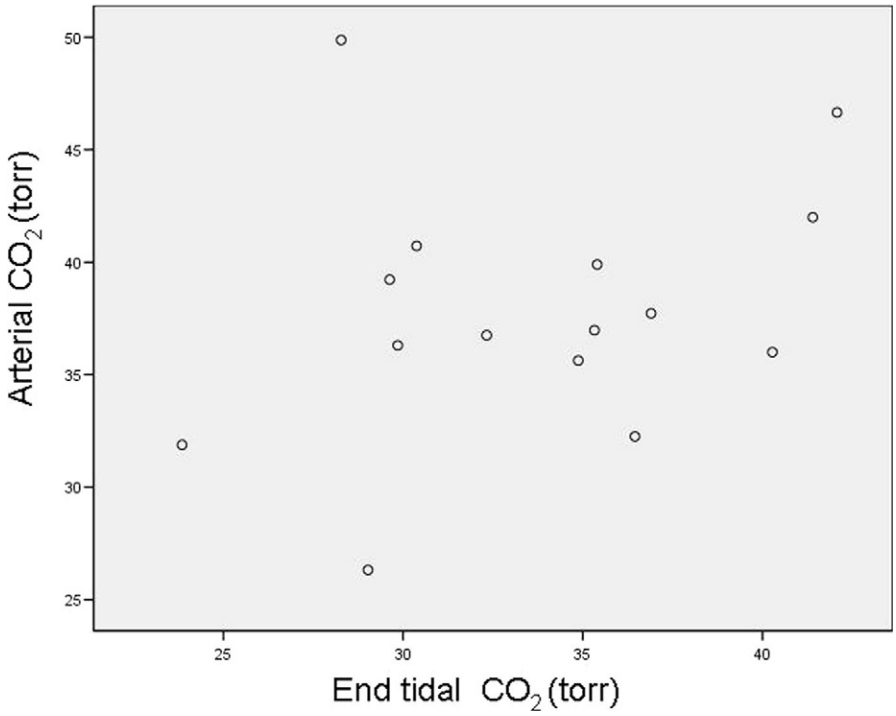

Figure 1. Scatter plot between the arterial and the end-tidal CO_2 values showing no relationship.

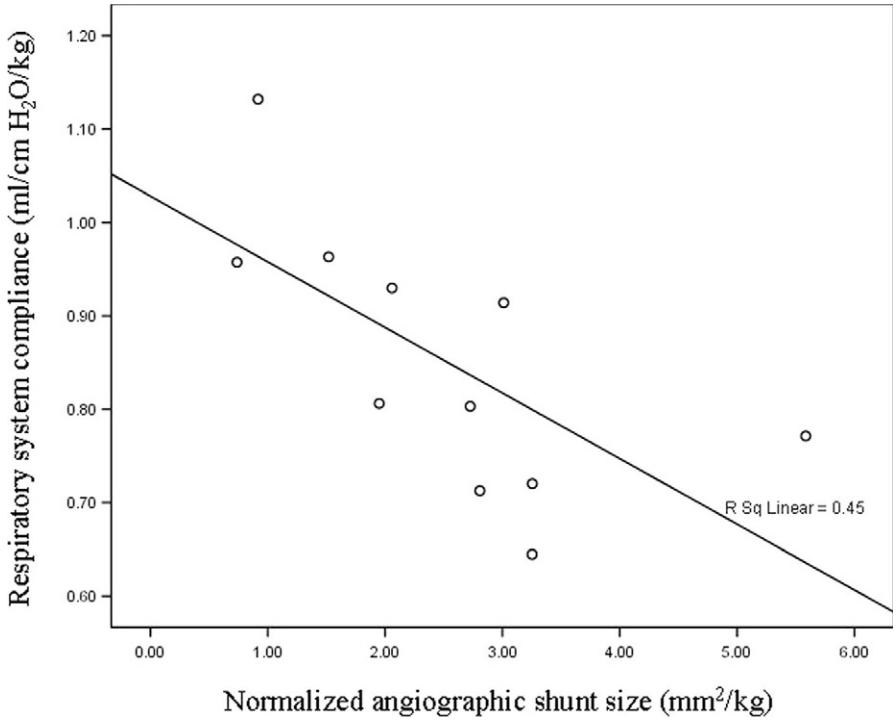

Figure 2. Scatter plot with regression line between the angiographically determined shunt sizes in radius squared normalized for body weight in kilogram and respiratory system compliance per kilogram.

with R_{rs} ($r = 0.72$, $r^2 = 0.52$, $p = 0.004$, n = 11) (Fig. 3). This means that patients with a larger heart had stiffer lungs and a higher respiratory resistance. There were eight chest radiographs categorized as hyperinflated and seven as normal, but there was no significant difference in lung function between these two groups.

Outcome Measures and Lung Function. A high physiologic dead space to tidal volume ratio was associated with a longer hospital stay ($r = 0.67$, $r^2 = 0.45$, $p = 0.006$, n = 15). We found no association between lung function variables and the length of respiratory support, but we had three missing values for the length of respiratory support.

DISCUSSION

There are two principle findings of this study in patients with univentricular hearts before the bidirectional cavopulmonary connection. The first is that lung function is related to the size of the shunt and the size of the heart. The second is that end-tidal CO_2 is not related to arterial CO_2.

In most cases, the infants with univentricular heart arrangements require the insertion of a shunt in the neonatal period to provide sufficient blood flow to the pulmonary circulation. It is important to choose the shunt size that provides adequate blood flow to the lungs for oxygenation while at the same time not overloading the pulmonary circulation or compromising the systemic circulation. We found that a larger shunt was associated with a lower respiratory compliance. The patients who had been given a larger shunt in the newborn period had stiffer lungs when measured at the time of catheterization even though most now had a pulmonary to systemic blood flow of <1. The effect of the surgical shunt size on lung function has to our knowledge not been published, but the hemodynamic consequence of different shunt sizes has been investigated. In the immediate postoperative period after the stage 1 Norwood operation, Photiadis et al (10) found better hemodynamics such as a lower atrial pressure and a higher arterial pressure in patients with a larger shunt. Mosca et al (11) examined the effect of changes in acid-base status and oxygen and found no effect on hemodynamic stability concluding that the major restriction to pulmonary blood flow is within the shunt. An experimental study by Kitaichi et al (12) investigated the effect of shunt size on pulmonary blood flow and found that a smaller shunt size to weight ratio gave an inverse relationship between pulmonary to systemic shunt ratio and arterial CO_2, whereas this relationship was not found with larger shunts. These studies exemplify the importance of the shunt size on pulmonary parameters and support our finding of an association between shunt size and compliance of the respiratory system. We did not find any correlation between the pulmonary to systemic shunt ratio and re-

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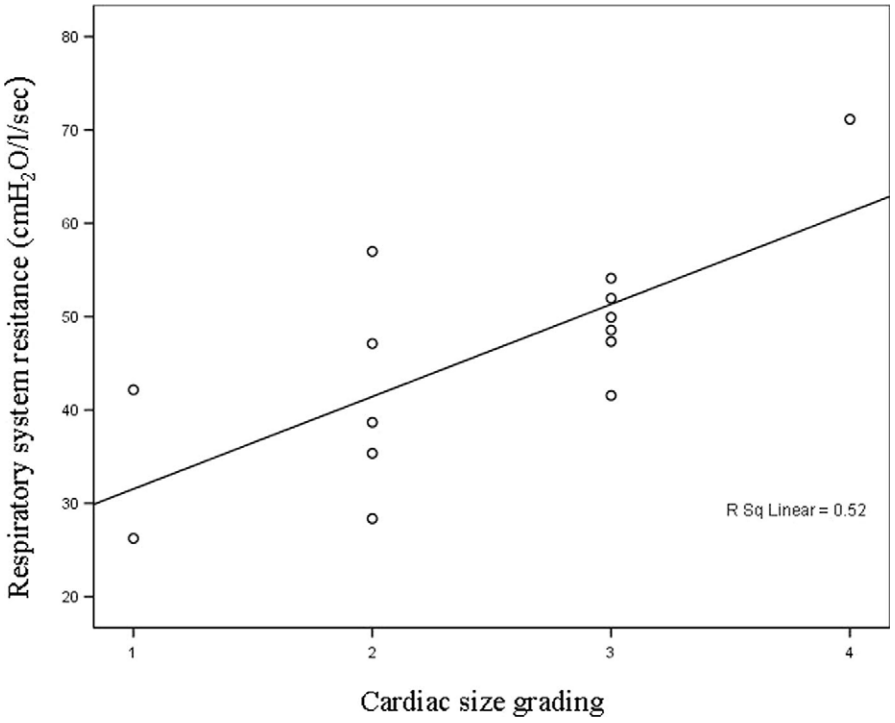

Figure 3. Scatter plot with regression line between the cardiac size grading and respiratory system resistance. Cardiac size is graded 1 for normal size, 2 for slightly enlarged, 3 for enlarged, and 4 for much enlarged.

spiratory compliance, supporting the view of Mosca et al (11). The above studies relate to the immediate postoperative period. Our study was performed several months after the operation when pulmonary to systemic blood flow was lower than in the neonatal period and it is possible that the association we found between a large shunt size and low compliance is related to an effect of an increased pulmonary to systemic shunt ratio in the period after the operation in the neonatal period (13). However, due to increased pulmonary vascular resistance which can occur in the immediate postoperative period some infants may have had less pulmonary blood flow than anticipated from the size of their shunt.

The compliance of the respiratory system was in the low to normal range in these patients with a mean pulmonary to systemic shunt ratio of <1. Other studies (14–16) with low pulmonary to systemic shunt ratio have found higher levels of compliance than we did. Many of our patients had been through respiratory support with oxygen therapy during their first operation and some had also had cardiopulmonary bypass. There is a possibility that these treatments were detrimental to their lung function leading to reduced respiratory compliance (17, 18). Relatively speaking the size of the shunt was larger soon after the operation than at the time of our measurements and the comparatively higher pulmonary blood flow in the newborn period may have a long lasting effect on lung function explaining the relatively low compliance that we found in our study.

Many of the children had cardiomegaly. This may affect the lung mechanics by reducing the intrathoracic space available to the lungs. In adults with chronic heart failure, an increased cardiac size has been found to be related to reduced lung volumes (19) and reduced spirometry values (20). We found that a larger heart size was related to a higher resistance of the airways and a lower compliance of lungs. It is possible that the heart as a space occupying lesion within the chest has this effect, since we found no relationship between lung mechanics and pulmonary vasculature. This may indicate that it is not the enlarged heart as part of heart failure with pulmonary congestion that results in this association with lung mechanics. However, on average the resistance of the respiratory system was similar to that found in other studies of children with congenital heart disease with decreased pulmonary blood flow (6, 21).

Our patients had a right-to-left shunt and most had reduced pulmonary blood flow. This can affect gas exchange. We measured a high dead space volume to tidal volume ratio, suggesting a higher than normal proportion of dead space ventilation. This increased dead space ventilation in cyanotic congenital heart disease supports findings by others (22). It may give rise to an abnormal gas exchange. We found a relationship between a higher dead space to tidal volume ratio and a longer hospital stay. A prognostic value of high dead space ventilation has been found in adult patients with acute respiratory distress syndrome (23) and in adult patients with heart failure (24). In infants, the dead space to tidal volume ratio can be used to predict successful extubation (25). There was no correlation between end-tidal CO_2 and arterial CO_2. This discrepancy between arterial and end-tidal CO_2 is especially important in patients with univentricular type malformations since respiratory manipulations are used to manage the patients in the postoperative period (26). It may, therefore, be advisable to rely on arterial CO_2 rather than end-tidal CO_2 values in patients with univentricular heart arrangements. The disagreement between arterial and end-tidal CO_2 in cyanotic patients supports findings by some (3, 27) but not by others (28). In the study by Tugrul et al (28) there was no significant correlation between arterial and end-tidal CO_2 before the insertion of a systemic-to-pulmonary artery shunt in patients with tetralogy of Fallot, but after the shunt insertion there was a correlation. Our study was performed several weeks after the shunt insertion. It may, therefore, be possible that the association between arterial and end-tidal CO_2 is lost as the patients "grow out of" their shunt. This is consistent with our finding that a lower pulmonary to systemic shunt ratio was associated with a larger arterial to end-tidal CO_2 difference. We found an inverse relationship between the arterial CO_2 and the pulmonary to systemic shunt ratio whereas no such relationship was found between the end-tidal CO_2 and the shunt ratio. This means that end-tidal CO_2 is no good estimate of the shunt ratio.

The main shortcoming of this study is the small number of patients. Norway has a population of only 4.7 million. Surgery for patients with univentricular heart physiology is performed exclusively at our hospital. However, the numbers of eligible infants were still small since the univentricular heart arrangements occur

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infrequently limiting the number of possible patients to be studied.

Another weakness is the subjective interpretation of the pediatric chest radiograph, especially regarding the assessment of pulmonary vasculature. We found slight to fair intraobserver agreement and slight interobserver agreement in the assessment of the pulmonary vasculature. The difficulty with the evaluation of the pediatric chest radiographs and in particular the interpretation of pulmonary blood flow, has been described by others (29, 30). The unreliability of the assessment of pulmonary vasculature may explain why we found no association between pulmonary vasculature markings and lung function.

It is common practice in infants to use uncuffed endotracheal tubes. This may lead to leakage that can influence the measurement of lung mechanics. We tried to minimize the effect of this problem on the study's results by excluding measurements where the leakage was >10%. This was the case for one patient measurement.

The patients all had a univentricular heart condition but with varying details in their anatomical diagnosis. It cannot be excluded that this may make the results less generally applicable. However, lung function is certainly more likely to be affected by the physiology rather than intracardiac anatomy.

CONCLUSION

We have found that lung mechanics is worse in patients with a larger surgical shunt and cardiomegaly. A large surgical shunt is related to a lower respiratory compliance and a large heart is related to an increased respiratory resistance. End-tidal CO_2 did not correlate with arterial CO_2 levels. This means that end-tidal CO_2 does not give an accurate estimate of arterial CO_2 in patients with univentricular heart physiology before the bidirectional cavopulmonary connection. End-tidal CO_2 should, therefore, not be used as a substitute for arterial CO_2 in this setting.

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