Pulmonary function in children with atrial septal defect before and after heart surgery

J Šulc, V Andrle, J Hruda, B Hučín, M Šamánek, A Zapletal

Abstract
Objective—To test the effect of heart disease and heart surgery on lung function.
Design—A pulmonary function study of children undergoing surgery for atrial septal defect (ASD).
Settings—University hospital.
Patients—26 children tested before surgery (at mean (SD) age 11.8 (3.8) years) and 24 patients tested 1.8 (0.2) years after surgical correction.
Methods—Lung volumes, lung elasticity, and airway patency indices were measured using standard techniques.
Results—Before surgery: pulmonary function test abnormalities were found in 18 of the 26 patients. Stiff lung was found in 12, lung hyperinflation in five, and indices of decreased airway patency in four. Total lung capacity decreased in only two patients. After surgery: pulmonary function test abnormalities were found in 12 of the 24 patients (informed consent not given for two patients). Stiff lung was detected in nine and indices of peripheral airway obstruction in four. Mean values of specific airway conductance and peak expiratory flow were all normal. Lung hyperinflation was found only in one of 24 patients. No correlation between perioperative events and pulmonary function test data was found.
Conclusions—Pulmonary function test abnormalities persist in half the patients almost two years after surgery for ASD. A decrease in the total frequency of pulmonary function test abnormalities (in 19% of the patients), with a decrease in stiff lung in 8% and lung hyperinflation in 15%, was not significant. Impairment of lung function related to ASD is associated with the disease itself rather than the surgical procedure.

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Keywords: atrial septal defect; heart surgery; pulmonary function; cardiopulmonary development

Lung function abnormalities in patients with atrial septal defect (ASD) have been reported in adults and adolescents as well as in children and infants. The most prominent abnormalities are lung volume restriction and changes in residual volume and functional residual capacity. Normal decreased airway patency is found. Non-uniform changes in lung elasticity also occur. Except in a study on adults, none of these studies has compared pulmonary function tests both before and a long time after heart surgery. Studies comparing lung function using a wide range of pulmonary function tests in children before and after surgery for ASD have not been reported. Our aim in this study was therefore to define the spectrum of pulmonary function test abnormalities in children and adolescents with ASD before heart surgery and over one year after correction.

Methods
PATIENTS AND SURGICAL PROCEDURES
Lung function was studied in 26 children (12 male, 14 female) before surgery for ASD (secundum type) and in 24 children after the surgery (informed consent was not obtained for the remaining two children). Apart from mild valvar pulmonary stenosis in two patients, no additional heart defects were present. Three patients had a history of repeated bronchitis or pneumonia. One patient was born during the 37th week of gestation weighing 1900 g. All the children were in excellent clinical condition at the time of the study (New York Heart Association class I). Informed consent was given on behalf of all the children.

Pulmonary function tests were done one to three days before surgery, which was performed at mean (SD) age 11.8 (3.8) years (median 12 years). The tests were repeated 1.79 (0.21) years later (median 1.8 years); at this time, mean height was 149.5 (20.1) cm and the patients were 14.0 (3.9) years old (median 14.8 years).

Left to right shunting before surgery was measured by radionuclide dilution in 25 of 26 patients and ranged between 14% and 67% of pulmonary blood flow (mean 45.2 (11.9)). At surgery, the ASD was closed either by direct suture or by a pericardial patch using
Pulmonary function in children with atrial septal defect

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tory flow–volume curves were used for the
which we derived an "envelope" curve rep-
tically good curves were recorded, from
after maximum inspiration. At least five
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(gave a value for "specific" lung compliance
slope of the middle linear part of pressure–
volume curves. Expressed per unit of TLC, Cst
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Simultaneous recording of transpulmonary
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Lung volumes
The mean values of VC, TLC, FRC, RV, and
RV/TLC did not differ from the reference
values. FRC/TLC was increased (p < 0.01)
(table 1).

Lung elasticity
The mean values of lung recoil pressure (Pst)
measured at 100% and 90% of total lung
capacity were significantly increased: lung
recoil measured at 100% TLC (Pst100) reached
123% of the reference value (p < 0.0005). Pst90
did not differ from the reference value. The
value of Cst/TLC was mildly decreased (91%
of predicted, p = 0.051) (table 1).

Airway patency
A significant decrease of sGaw to 72 (18)% of
predicted value (p < 0.0001) was found. Mean
values of PEFR and MEF50VC/TLC, MEF25VC/TLC,
and MEF50VC/TLC/TLC were normal (table 1).

Frequency of abnormal lung function tests
Abnormal lung function tests (that is, tests
deviating by more than 2 SD from the mean
normal value) were found in 18 of the 26
patients (69.2%) (table 2). Lung recoil pressure,
indicating stiff lung, was significantly
increased in 12 patients (46.2%) and decreased
in two (7.7%), respectively. Maximum expira-
tory flow rates—indicating peripheral airway

LUNG FUNCTION TESTS
Functional residual capacity was measured at
end expiration as thoracic gas volume (TGV)
in a body plethysmograph. Static lung volumes
were derived from the measurements of TGV
and from lung volumes calculated from the
expiratory pressure–volume curve (see below).
The highest vital capacity (VC) and inspiratory
capacity (IC) values, taken as representative
values in a particular subject, were used for the
calculations. Total lung capacity (TLC) was
obtained from the TGV plus IC, and the
residual volume (RV) was calculated as TLC
minus VC.

Lung elasticity was assessed from the expira-
tory pressure–volume curves obtained as a
simultaneous recording of transpulmonary
pressure (measured as the difference between
oesophageal and mouth pressures) and lung
volume changes. A latex oesophageal balloon
(wall thickness up to 0.1 mm, length 100 mm)
was situated in the lower third of the
oesophagus. The pressure–volume curves
were recorded under quasi-static conditions during
very slow expiration, with airflow being inter-
rupted by shutter valve for 0.3 seconds. At least
five technically good pressure–volume curves
were obtained from each patient. Lung recoil
pressure was measured from the pressure–
volume curves at 100%, 90%, and 60% of
TLC. Static lung compliance (Cst), another
index of lung elasticity, was obtained from the
slope of the middle linear part of pressure–
volume curve. Expressed per unit of TLC, Cst
gave a value for “specific” lung compliance
(Cst/TLC).

Airway resistance (Raw) was measured dur-
ing quiet breathing simultaneously with TGV
in a body plethysmograph. Raw was converted
to its inverse value (that is, airway conduc-
tance) and expressed per unit of TGV as
specific airway conductance (sGaw). Maxi-
mum expiratory flow–volume curves were
obtained by performing a complete and rapid
expiration to residual volume level immediately
after maximum inspiration. At least five
technically good curves were recorded, from
which we derived an “envelope” curve rep-
resentative of each subject. Maximum expira-
tory flow–volume curves were used for the
assessment of forced vital capacity (FVC), peak
expiratory flow rate (PEF), maximum expira-
tory flow rates at 25% and 50% of forced vital
capacity (MEF25VC, MEF50VC), and at 60% of
total lung capacity (MEF60TLC). In order to
correct the absolute values of flow rates (litre/s)
for lung size, ratios of maximum expiratory
flow rates and TLC were calculated.

The results of pulmonary function test
measurements are expressed as mean (SD) and
as percentage of the predicted values. As refer-
ence values, we used pulmonary function test
indices from a healthy population matched for
height, sex, and age measured using the
same methods in the same laboratory.22 To
compare preoperative and postoperative data,
we calculated predicted values in both testing
sessions.

STATISTICS
Differences between the parametric data were
tested by Student’s paired t test where possible
or by the unpaired t test. Non-parametric data
were compared by the Mann–Whitney test.
The level of statistical significance was set at
p = 0.05. We examined the correlation be-
tween pulmonary function tests and preopera-
tive data (magnitude of the left to right shunt),
perioperative data (duration of cardiopulmon-
ary bypass, duration of aortic cross clamp), and
postoperative data (duration of ventilation, interval between surgery and testing). The cor-
relation between the data was tested by the
Pearson product moment correlation test.

Results
PULMONARY FUNCTION TEST MEASUREMENTS
BEFORE SURGERY
Lung volumes
The mean values of VC, TLC, FRC, RV, and
RV/TLC did not differ from the reference
values. FRC/TLC was increased (p < 0.01)
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in two (7.7%), respectively. Maximum expira-
tory flow rates—indicating peripheral airway

Postoperative course
The early postoperative course was unevent-
ful in the majority of the patients. One was
reintubated and ventilated for six hours
because of acute respiratory insufficiency and
pneumopericardium during the first postopera-
tive day. Three other patients developed a
postpericardiotomy syndrome, atelectasis of
the right middle lobe, and pneumopericar-
dium, respectively. All these perioperative
events recovered completely.

Cardiopulmonary bypass
A median age of 6.1 (1.1) years was used for
an aortic cross clamp was in place for 12.7
(9.5) minutes (range 0 to 40 minutes). Almost
all patients were extubated in the theatre;
therefore the duration of postoperative me-
chanical ventilatory support was only 1.3 (1.9)
hours, range 0 to 7 hours.

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dium, respectively. All these perioperative
events recovered completely.
Table 1 Pulmonary function before and after surgery for atrial septal defect

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before surgery (n = 26)</th>
<th>After surgery (n = 24)</th>
<th>Postoperative v preoperative values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Predicted</td>
<td>p value v predicted</td>
<td>Mean</td>
</tr>
<tr>
<td>VC (ml)</td>
<td>96.9 13.8</td>
<td>NS</td>
<td>97.1 14.5</td>
</tr>
<tr>
<td>FRC (ml)</td>
<td>103.3 14.2</td>
<td>NS</td>
<td>81.0 18.3</td>
</tr>
<tr>
<td>TLC (ml)</td>
<td>98.4 10.1</td>
<td>NS</td>
<td>95.4 12.4</td>
</tr>
<tr>
<td>RV (ml)</td>
<td>104.6 17.6</td>
<td>NS</td>
<td>90.3 24.9</td>
</tr>
<tr>
<td>RV/TLC (%)</td>
<td>107.5 19.2</td>
<td>NS</td>
<td>97.9 19.7</td>
</tr>
<tr>
<td>FRC/TLC (%)</td>
<td>105.9 9.1</td>
<td>&lt; 0.01</td>
<td>94.2 10.5</td>
</tr>
<tr>
<td>Cst/TLC (ml.cm H₂O⁻¹.l⁻¹)</td>
<td>90.9 23.0</td>
<td>NS</td>
<td>87.6 20.5</td>
</tr>
<tr>
<td>Pst100%TLC (cm H₂O)</td>
<td>123.3 25.4</td>
<td>&lt; 0.0005</td>
<td>131.8 25.2</td>
</tr>
<tr>
<td>Pst90%TLC (cm H₂O)</td>
<td>109.8 22.8</td>
<td>&lt; 0.05</td>
<td>116.6 20.5</td>
</tr>
<tr>
<td>Pst60%TLC (cm H₂O)</td>
<td>110.7 38.1</td>
<td>NS</td>
<td>127.2 36.3</td>
</tr>
<tr>
<td>sGaw (cm H₂O⁻¹.s⁻¹)</td>
<td>72.0 17.9</td>
<td>&lt; 0.0001</td>
<td>101.3 30.4</td>
</tr>
<tr>
<td>PEFR (l.s⁻¹)</td>
<td>95.0 17.1</td>
<td>NS</td>
<td>102.7 17.7</td>
</tr>
<tr>
<td>MEF₂₅%VC/TLC (l.s⁻¹.l⁻¹)</td>
<td>102.5 28.9</td>
<td>NS</td>
<td>103.7 36.3</td>
</tr>
<tr>
<td>MEF₅₀%VC/TLC (l.s⁻¹.l⁻¹)</td>
<td>109.3 20.4</td>
<td>NS</td>
<td>109.6 23.4</td>
</tr>
<tr>
<td>MEF₆₀%TLC/TLC (l.s⁻¹.l⁻¹)</td>
<td>105.4 25.0</td>
<td>NS</td>
<td>113.7 27.6</td>
</tr>
</tbody>
</table>

Cst/TLC, static compliance corrected for total lung capacity; FRC, functional residual capacity; MEF, maximum expiratory flow (corrected for total lung capacity); PEFR, peak expiratory flow rate; Pst, static lung recoil pressure; Raw, airway flow resistance; RV residual volume; sGaw, specific airway conductance; TLC, total lung capacity; VC, vital capacity.

Lung recoil pressure was increased in nine patients (37.5%) and decreased in one (4.2%). Maximum expiratory flow rates were reduced in four patients (16.7%). No decreased specific airway conductance or peak expiratory flow rates were found. Total lung capacity was significantly decreased in three patients (8.3%). The FRC/TLC and RV/TLC ratios were increased in only one patient (4.2%).

Comparison of preoperative and postoperative pulmonary function test data
The overall frequency of abnormal preoperative and postoperative pulmonary function tests (18/26 (69.2%) v 12/24 (50.0%)) did not differ significantly (table 2).

Lung elasticit
Values of FRC, RV, and FRC/TLC and RV/TLC ratios decreased significantly (p < 0.0001, p < 0.0001, and p < 0.05, respectively). There was a mild decrease in TLC with no change in vital capacity (table 1).

Lung elasticity
No significant changes in lung recoil or static lung compliance were found (table 1).

Airway patency
A significant increase in sGaw (p < 0.0005) and PEFR (p < 0.05) was found. Values of MEF₁₀₀%TLC remained unchanged in all cases (table 1).

Relations between preoperative pulmonary haemodynamics, perioperative events, and lung function
Age at surgery
There was a positive linear correlation of postoperatively measured TLC and VC with age at surgery (r = 0.461, p < 0.03 and r = 0.648, p < 0.002, respectively). There was a positive linear correlation of postoperative MEF₁₀₀%TLC/TLC and PEFR with age at surgery (r = 0.450, p < 0.03 and r = 0.514, p < 0.02, respectively). Postoperative elastic recoil at 90% TLC correlated inversely with age at surgery (r = −0.575, p < 0.01).

Table 2 Frequency of abnormal lung function tests before and after surgery for atrial septal defect

<table>
<thead>
<tr>
<th>Group</th>
<th>Before (n = 26)</th>
<th>After (n = 24)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>%</td>
<td>n</td>
</tr>
<tr>
<td>Lung volume restriction</td>
<td>2</td>
<td>7.7</td>
<td>3</td>
</tr>
<tr>
<td>Hyperinflation</td>
<td>5</td>
<td>19.2</td>
<td>1</td>
</tr>
<tr>
<td>Stiff lung</td>
<td>12</td>
<td>46.2</td>
<td>9</td>
</tr>
<tr>
<td>Emphysematous lung</td>
<td>2</td>
<td>7.7</td>
<td>1</td>
</tr>
<tr>
<td>Airway obstruction</td>
<td>4</td>
<td>15.4</td>
<td>0</td>
</tr>
<tr>
<td>Central</td>
<td>4</td>
<td>15.4</td>
<td>4</td>
</tr>
<tr>
<td>Peripheral</td>
<td>18</td>
<td>69.2</td>
<td>12</td>
</tr>
</tbody>
</table>

No significant changes in lung recoil or static lung compliance were found (table 1).

Age at surgery
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Magnitude of left to right shunt

No correlation between the preoperative left to right shunt and preoperative or postoperative pulmonary function test data was found.

Perioperative events

There was no correlation between duration of cardiopulmonary bypass, aortic cross clamp, or ventilation and preoperative or postoperative pulmonary function test data.

Pulmonary function tests

There was a negative correlation between postoperative elastic recoil measured at 60% TLC and RV/TLC ($r = -0.489, p < 0.05$), and a negative correlation between elastic recoil measured at 100% TLC and FRC/TLC ($r = -0.478, p < 0.03$).

Discussion

In our previous paper, we found pulmonary function test abnormalities in 35 of 74 patients (47%) tested five years after heart surgery for ASD. These findings were surprising in view of the excellent clinical outcome of the surgery at the time of testing. In the present series—which was done with completely different subjects than in our previous study—the overall frequency of pulmonary function test abnormalities after surgery lessened slightly, from 69% to 50% of patients. Similarly, only discrete postoperative changes in dynamic lung volumes have been documented elsewhere.

A reduction in TLC (a measure of lung size) was found both preoperatively and after surgery in only 7.7% and 8.3% of patients, respectively. This is in line with their excellent clinical condition. The most frequent abnormality we found in the present study was lung stiffness. Non-uniform changes in lung elasticity found in previous studies are not surprising, because (except in those by DeTroyer et al and Sulc et al) dynamic lung compliance was usually the only indicator considered. Increased lung recoil pressure measured at different levels of TLC is a more sensitive index for detecting abnormalities of lung elasticity. An even more pronounced increase in lung stiffness (assessed by the same method) was found long term in patients after surgery for simple transposition of the great arteries and ventricular septal defect. Changes in the elastic properties of the lungs before surgery could be caused by increased pulmonary blood flow and volume and engorgement of the capillary network. Persistence of stiff lung indices in other types of congenital heart defect with high pulmonary blood flow can result from vascular changes leading to progressive remodelling of the lung parenchyma, even with fibrotic changes.

The different responses of fetal compared with adult vascular smooth muscle cells to high pulmonary blood flow and pressure could also influence the outcome. Long term changes in pulmonary blood flow could affect the fragile balance between hypercompliant pulmonary parenchyma and hypocompliant peribronchial parenchyma, and might lead to reorganisation of related pulmonary parenchymal structures.

Any form of adaptation of the lung parenchyma and pulmonary vasculature to a new haemodynamic status should also be considered.

The surgical procedure itself is unlikely to contribute substantially to increased lung stiffness postoperatively. The patients were exposed by central sternotomy to a very short period of cardiopulmonary bypass and ventilation, avoiding all but the most trivial damage to the lungs. Under such conditions, only short term changes caused by a temporary increase of extravascular lung water and relative lymphatic insufficiency have been found. There are confirmatory reports on the absence of changes in the static compliance of the respiratory system during cardiopulmonary bypass in children operated on for ASD.

It is difficult to draw any conclusion about possible anatomical abnormalities of the lung parenchyma causing stiff lungs because no open lung or transbronchial biopsies were available in our patients. We might hypothesise that the normal growth of the elastic and collagen tissue during the fetal and perinatal period may be altered by abnormal pulmonary haemodynamics influencing lung development up to the time of heart surgery. 

Hyperinflation, assessed by the increased ratios of FRC/TLC and RV/TLC, was seen preoperatively in 19% of our patients, compared with 4% postoperatively. Our postoperative data are similar to those of adults with uncorrected atrial septal defects. Generally, a higher preoperative pulmonary blood flow might contribute to hyperinflation. The postoperative reduction in hyperinflation was inversely correlated with the slight increase in the frequency of stiff lung. Therefore we might hypothesise a beneficial effect of a stiffer lung, which could result in a lesser degree of hyperinflation. Previous findings of a high frequency of stiff lung (24/74 patients (32%)) and low incidence of hyperinflation (< 5% of the patients) in another group of patients studied more than five years after correction of ASD tend to confirm this suggestion.

Similarly, a reduced maximum expiratory flow rate at lower levels of vital capacity, indicating peripheral (smaller) airway obstruction, was found before as well as after surgery in only 15% and 17% of our patients, respectively. This may be caused by the harmful impact of increased pulmonary blood flow and volume on small airways. However, the mean values of these indices were “supranormal” (reaching 103–109% and 104–113% of predicted, respectively), implying on average a normal peripheral airway patency in the group as a whole. An observation of preoperatively decreased airway conductance, indicating obstruction of the central (larger) airways, in 15% of our patients could be related to abnormal haemodynamics and repeated preoperative infections. Peripheral airway obstruction was detected preoperatively in only one of the three patients with a history of repeated bronchitis. In none of them, however, did surgery related events lead to an increase in airflow limitation. Moreover, no correlation between the duration...
of ventilation (up to seven hours) and airway patency indices was found which might suggest a deleterious effect of tracheal intubation itself. The only deterioration in postoperative pulmonary function tests (development of peripheral airway obstruction and hyperinflation) was found in a boy who was reintubated and ventilated for a short period for respiratory insufficiency.

A negative correlation between age at surgery and postoperative lung recoil, and a positive correlation between age at surgery and postoperative airway patency index may also indicate that the earlier the surgery, the “worse” the airway patency. There have been similar findings in patients after atrial correction for simple transposition. We hypothesise that even a successful repair reversing all haemodynamic effects could not reverse the harmful impact of abnormal pulmonary haemodynamics on the developing lung. These findings have, however, to be interpreted cautiously because our group represents one of the first containing patients operated on as late as a mean age of 11.8 years. At present patients are scheduled for surgery for ASD at the age of 1 to 4 years. It may thus be the case that those patients who have remained unoperated or even undiagnosed until an older age were those with less significant impairment of both cardiac and pulmonary function.

CONCLUSIONS
Surprisingly, the surgical repair of ASD did not result in substantial improvement in postoperative pulmonary function tests. When comparing preoperative with postoperative data, we found a small decrease in the overall frequency of pulmonary function test abnormalities, with little reduction in the frequency of stiff lung or indices of lung hyperinflation. The surgical procedure itself, and the perioperative and early postoperative factors, did not produce any marked change in the frequency and severity of pulmonary function test abnormalities. This has implications for patients receiving surgery for more severe forms of congenital heart disease, where the overall incidence of abnormal postoperative pulmonary function test results is substantially higher (using similar surgical procedures). Therefore this rather prominent degree of lung dysfunction is probably caused by events unrelated to perioperative or postoperative factors.

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