Cardiac output and pulmonary gas exchange at maximal exercise after atrial redirection for complete transposition

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Aims To assess the determinants of exercise capacity and exercise oxygenation after atrial redirection for complete transposition.

Methods and Results At graded bicycle ergometry, including respiratory and arterial blood gas analyses, intra-arterial blood pressure recording, and cardiac output determination (dye-dilution technique), we tested 17 post-Mustard/Senning patients, 8.9–22.0 years old (mean 14.5, SD 4.0). Reference data were obtained by similar methods. At maximal exercise, oxygen uptake (29.6 ml·kg⁻¹·min⁻¹) and heart rate (167 beats·min⁻¹) were low (P<0.001). Right-to-left shunts were detected in five patients. Arterial oxygen partial pressure and saturation fell in all subjects (P<0.0001). In 15/16 (94%) the alveolar–arterial oxygen partial pressure difference was >+2 SD. In 13/15 (87%) stroke volumes fell during exercise. Cardiac output per oxygen uptake was low (P<0.0001), which implies a high arteriovenous oxygen difference and a low mixed venous oxygen content at peak exercise.

Conclusion The low exercise capacity was caused by a combination of low maximally attained heart rate and falling stroke volumes. The impaired arterial oxygenation may be caused by a combination of pulmonary ventilation/perfusion mismatch, a low mixed venous content and atrial shunting in some patients.

Key Words: Mustard operation, Senning operation, cardiac output, exercise test, gas exchange.

Introduction

Decreased exercise capacity is a frequent finding after atrial redirection (Mustard and Senning operation) for complete transposition[1–5]. This low exercise capacity has mainly been attributed to a diminished cardiac output response due to impaired ventricular performance[1–3], although systemic ventricular dysfunction at rest, or even ejection fraction response to exercise, appears to be a poor predictor of exercise capacity[1,2,6]. Most patients also have a low maximal heart rate, but this does not appear to be the main contributor to the low performance either[1,3,5]. Moreover, several patients demonstrate exercise desaturation, which is presumed to be caused by atrial shunting, although some patients without baffle defects desaturate during exercise as well[1,4]. The role of pulmonary gas exchange in the exercise physiology of these patients has not been thoroughly discussed. In order further to elucidate the determinants of exercise capacity and exercise oxygenation, we have conducted a complete cardiopulmonary exercise test, including simultaneous recording of cardiac output and blood pressure, and analysis of respiratory and arterial blood gases in a cohort of post-Mustard and post-Senning patients.

Methods

Patients
We have surveyed all the patients born with complete transposition in western Sweden during the early era of atrial redirection (1964–1983)[7], including a thorough follow-up of all 32 long-term survivors after atrial redirection at our institution (Göteborg)[8–10]. All the survivors had a preliminary maximal exercise test to assess the ability to conform to a protocol for a more thorough assessment of the physiological reactions to exercise. Eight patients below 10 years of age with a generally good clinical status (post-Senning patients) and seven older patients (mainly post-Mustard patients) with considerable sequelae (severe pulmonary
hypertension, hemiparesis, pacemaker-dependent atrioventricular block, severely impaired cardiac function, and exercise cyanosis) were found to be unable to participate. The remaining 13 male and four female patients participated in the study. The mean age was 14·5 years (SD 4·0). There were 11 post-Mustard patients, age 12·0–22·0 years, and six post-Sennling patients, age 8·9–12·1 years. None had a significant ventricular septal defect at the operation. All were without cardiac symptoms and took part in regular school or vocational activities. Most were rather sedentary without cardiac symptoms and took part in regular school or vocational activities. Most were rather sedentary. Antiarrhythmic treatment in two subjects was discontinued 2 days before the test. During the same week as the exercise study, the patients had a complete haemodynamic investigation. One boy had tricuspid regurgitation. One patient had a large bidirectional atrial shunt and was excluded from most analyses. Another had a small shunt detectable from oxygen saturation data. Seven additional subjects had tiny baffle gaps (catheter passed or trivial contrast leakage at the invasive haemodynamic investigation). One boy had tricuspid regurgitation secondary to an intermittent atrioventricular block and was excluded from all analyses involving cardiac output. No other arrhythmias were present during the investigation. Pulmonary hypertension was defined as a systolic pulmonary artery pressure of 31–50 mmHg (mild), 51–70 mmHg (moderate), and >70 mmHg (severe).

Methods

The study was approved by the medical ethics committee at the University of Göteborg and informed consent was obtained from all the participants. Data were obtained at rest in the supine position and during exercise in the sitting position on an electrically-braked bicycle ergometer (Elema, Stockholm) at a pedalling rate of 60 revolutions per minute, using a steady-state protocol with increments in load every 6–8 min adjusted according to the results at the preliminary test as to obtain two to three submaximal loads before maximum, which was defined as the highest endurable load for at least 6 min.

Expiratory air was collected in Douglas bags for 10 min at rest and for at least 1 min at the end of each work-load. Volumes were measured in a balanced Tissot spirometer. Oxygen and carbon dioxide content were determined by micro-Scholander analysis[11]. Double determinations were made on each bag: there was no significant difference between the two analyses (t-test, \( P=0·91 \)). Cardiac output was determined twice at rest and after 4 min of exercise at each work level from dye-dilution curves recorded with a Brechtelsbauer spectrophotometer (Brechtelsbauer, Munich, Germany). Cardiogreen, 2·5 or 5 mg . ml\(^{-1}\) (Hynson, Westcott & Dunning, Baltimore, U.S.A.), in carefully calibrated syringes was rapidly injected into a cubital vein. Radial artery blood was drawn at a constant speed of 38 ml . min\(^{-1}\) and reinfused after each withdrawal. Blood for four-point calibration was drawn immediately after the exercise test. The curve area was calculated by manual semilogarithmic plotting, extrapolation and planimetry[12]. Of 126 recordings, 16 were discarded for technical reasons. In 45 pairs of recordings at the same work level, the second cardiac output determination was a mean of 3·0% higher than the first (SD 8·5; t-test, \( P=0·05 \)). Heart rate was recorded from electrocardiographic tracings every minute and during dye injection. Stroke volume was calculated from the formula:

\[
\text{Stroke volume} = \frac{\text{Cardiac output}}{\text{Heart rate}} \quad (1)
\]

Mean values for cardiac index and stroke volume index, obtained using the formula for body surface developed by Haycock et al[13], were used for the analysis. The arteriovenous oxygen difference was calculated from the formula:

\[
\text{Arteriovenous oxygen difference} = \frac{\text{Oxygen uptake}}{\text{Cardiac output}} \quad (2)
\]

The magnitude of a right-to-left shunt at dye dilution (percentage of systemic blood flow) was estimated using the forward triangle method described by Rudolph[14].

Arterial blood pressure was recorded from the radial artery at rest and the end of each work level with a pressure transducer. Respiratory rate was counted every second minute and during air collection. Samples for arterial blood gas and haemoglobin were obtained during air collection and analysed using conventional analysers (Radiometer, Copenhagen). The arterial oxygen content was calculated from the haemoglobin concentration, the oxygen saturation and a combining factor of 1·34. Blood lactate was analysed at rest and at the end of each level of work using an enzymatic method.

Standard equations were used for calculating pulmonary gas exchange[15,16]. The dead space of the equipment was subtracted. The alveolar carbon dioxide partial pressure was assumed to be equal to the arterial carbon dioxide partial pressure.

Statistical analysis

Non-parametric tests were used for the statistical analysis: Wilcoxon rank sum test for paired comparisons and
### Table 1  Cardiopulmonary exercise test after atrial redirection for complete transposition. Individual data at maximal work

<table>
<thead>
<tr>
<th>Operation</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Clinical status*</th>
<th>Baffle defect **</th>
<th>R–L shunt</th>
<th>True maximum†</th>
<th>VO₂ (ml kg⁻¹ min⁻¹)</th>
<th>Heart rate (kPa)</th>
<th>PaO₂ (%)</th>
<th>SaO₂ (%)</th>
<th>PAaO₂ (kPa)</th>
<th>Stroke volume (% of value at rest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senning</td>
<td>f</td>
<td>8·9</td>
<td>—</td>
<td>No</td>
<td>—</td>
<td>27</td>
<td>189</td>
<td>10·5</td>
<td>94·4</td>
<td>5·5</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Senning</td>
<td>m</td>
<td>9·6</td>
<td>—</td>
<td>No</td>
<td>—</td>
<td>37</td>
<td>186</td>
<td>10·7</td>
<td>94·4</td>
<td>4·3</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Senning</td>
<td>f</td>
<td>10·6</td>
<td>—</td>
<td>Yes</td>
<td>—**</td>
<td>28</td>
<td>176</td>
<td>10·0</td>
<td>93·0</td>
<td>5·7</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Senning</td>
<td>m</td>
<td>11·0</td>
<td>Exercise AV block, TR</td>
<td>No</td>
<td>—</td>
<td>29</td>
<td>84</td>
<td>9·8</td>
<td>92·7</td>
<td>4·9</td>
<td>4·9</td>
<td></td>
</tr>
<tr>
<td>Senning</td>
<td>m</td>
<td>11·6</td>
<td>SVD</td>
<td>tiny**</td>
<td>Yes</td>
<td>38</td>
<td>181</td>
<td>8·6</td>
<td>90·0</td>
<td>7·4</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>12·0</td>
<td>—</td>
<td>No</td>
<td>—</td>
<td>30</td>
<td>143</td>
<td>7·8</td>
<td>88·9</td>
<td>8·2</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>12·1</td>
<td>—</td>
<td>tiny**</td>
<td>Yes</td>
<td>37</td>
<td>182</td>
<td>7·1</td>
<td>82·5</td>
<td>8·6</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>13·2</td>
<td>Obesity</td>
<td>No</td>
<td>—</td>
<td>18</td>
<td>162</td>
<td>10·7</td>
<td>94·6</td>
<td>3·4</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>14·5</td>
<td>SVD</td>
<td>tiny</td>
<td>No</td>
<td>35</td>
<td>165</td>
<td>9·8</td>
<td>93·1</td>
<td>6·2</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>14·8</td>
<td>SVD, moderate PHT</td>
<td>small**</td>
<td>Yes</td>
<td>21</td>
<td>174</td>
<td>6·2</td>
<td>77·7</td>
<td>9·4</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>14·9</td>
<td>SVD, tracheal stenosis</td>
<td>No</td>
<td>—</td>
<td>31</td>
<td>160</td>
<td>9·7</td>
<td>91·6</td>
<td>2·9</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>15·2</td>
<td>SVD, obliterated SVC</td>
<td>tiny</td>
<td>Yes</td>
<td>39</td>
<td>169</td>
<td>11·1</td>
<td>94·2</td>
<td>4·5</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>16·1</td>
<td>SVD</td>
<td>large**</td>
<td>Yes</td>
<td>25</td>
<td>185</td>
<td>6·1</td>
<td>73·6</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>f</td>
<td>19·9</td>
<td>Mild mental retardation</td>
<td>No</td>
<td>—</td>
<td>23</td>
<td>155</td>
<td>10·7</td>
<td>94·5</td>
<td>3·5</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>f</td>
<td>20·1</td>
<td>SVD, mild anaemia</td>
<td>tiny</td>
<td>Yes</td>
<td>21</td>
<td>171</td>
<td>8·5</td>
<td>90·3</td>
<td>7·7</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>f</td>
<td>20·3</td>
<td>Severe obstructed SVC, moderate PHT</td>
<td>Yes</td>
<td>—</td>
<td>18</td>
<td>169</td>
<td>8·2</td>
<td>87·5</td>
<td>7·1</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Mustang</td>
<td>m</td>
<td>22·0</td>
<td>Smoker</td>
<td>tiny</td>
<td>Yes</td>
<td>46</td>
<td>190</td>
<td>11·0</td>
<td>94·1</td>
<td>4·2</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

*Omitted: Trivial TR, sinus node dysfunction with bradycardia, mild SVC obstruction, mild right or left ventricular outflow obstruction, mild PHT.

**Shunt of 0.8–1.5% as detected from dye-dilution curves.

†Defined as B-Lactate > 7 mM 1⁻¹ or RER > 1.00 at maximum[^17].

AV = atrioventricular; PAo₂ = alveolar-arterial oxygen partial pressure difference; PHT = pulmonary hypertension; SVC = superior caval vein; SVD = moderate systemic ventricular dysfunction; TR = moderate tricuspid regurgitation. See also legend to Table 2.
the Mann-Whitney U-test for unpaired. Correlations were assessed using simple correlation with Fisher’s r to z formulation. The significance level was set at $P < 0.05$.

### Results

Individual data at maximal work are presented in Table 1. Group data at rest and at maximal work are presented in Table 2.

### Exercise data

Before maximum, one submaximal load was obtained in three subjects and two to three submaximal loads in the remainder. Fourteen subjects performed equal to, or better than, the preliminary test. At maximal work, nine subjects fulfilled the criteria for ‘true’ maximum as defined[17].

The maximal oxygen uptake (29.6 ml·kg$^{-1}$·min$^{-1}$) was low compared with normal data ($P < 0.001$[18,19]; in 11 subjects (65%) it was below – SD. The maximal heart rate (167 beats·min$^{-1}$) was low$^{19,20}$ ($P < 0.001$), most notably in a boy with second-to third-degree atrioventricular block during exercise; only four (24%) had values within the normal range ($\geq -2$ SD). During exercise, right-to-left shunts in the range of 8–15% could be detected on dye-dilution curves in five cases, one of whom had no previously known baffle-gap (Table 1).

### Cardiopulmonary exercise test after atrial redirection for complete transposition, n=17. Data at rest and maximal exercise

<table>
<thead>
<tr>
<th>Load (W·kg$^{-1}$·BW)</th>
<th>Rest (supine)</th>
<th>Maximal exercise (sitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>SD</td>
<td>range</td>
</tr>
<tr>
<td>0</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>68</td>
<td>11</td>
<td>54–95</td>
</tr>
<tr>
<td>38.8</td>
<td>6.8</td>
<td>31.4–56.8</td>
</tr>
<tr>
<td>0.36</td>
<td>0.06</td>
<td>0.27–0.48</td>
</tr>
<tr>
<td>0.87</td>
<td>0.10</td>
<td>0.77–1.11</td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.5–1.4</td>
</tr>
<tr>
<td>4.8</td>
<td>1.1</td>
<td>3.4–6.4</td>
</tr>
<tr>
<td>12.1</td>
<td>1.4</td>
<td>9.4–14.5</td>
</tr>
<tr>
<td>96.6</td>
<td>1.2</td>
<td>93.6–98.2</td>
</tr>
<tr>
<td>3.3</td>
<td>0.7</td>
<td>2.2–4.6</td>
</tr>
<tr>
<td>49.6</td>
<td>12.7</td>
<td>28.5–69.4</td>
</tr>
<tr>
<td>4.9</td>
<td>0.3</td>
<td>3.3–8.5</td>
</tr>
<tr>
<td>88</td>
<td>16</td>
<td>52–119</td>
</tr>
<tr>
<td>28.2</td>
<td>8.7</td>
<td>13.7–44.0</td>
</tr>
</tbody>
</table>

* n=16. ** n=15.

avO2diff = arteriovenous oxygen difference; BPm = mean arterial blood pressure; CI = cardiac index; PaO2 = arterial oxygen partial pressure; RER = respiratory exchange ratio; SaO2 = arterial oxygen saturation; SVI = stroke volume index; TSVR = total systemic vascular resistance; VD/VT = physiological dead space to tidal volume; VCO2 = carbon dioxide production; VE/VO2 = ventilatory equivalent for oxygen; VO2 = oxygen uptake.

### Pulmonary gas exchange and blood gases

At rest, most subjects hyperventilated, i.e. most had a ventilatory equivalent for oxygen of above 30 and a somewhat low arterial carbon dioxide partial pressure. The ventilatory equivalent for oxygen fell in all subjects at the start of exercise and rose again concomitant to higher work rates, with the exception of a boy with tracheal stenosis, who displayed hypoventilation with hypercapnea at peak exercise. The mean physiological dead space to tidal volume fell from 0.36 at rest to 0.25 at peak exercise. In a young man with mild mental retardation and a good haemodynamic status and in both subjects with moderate pulmonary hypertension, one of whom had a small atrial shunt at rest, there was an increasing dead space to tidal volume during exercise, suggesting a ventilation/perfusion mismatch[21]. In the remaining 13 subjects, the mean dead space to tidal volume at maximal exercise was 0.21 (SD 0.04), which is at the upper limit of normal values for adults[22] but considerably higher than the 0.08 which has been reported in healthy 11–13-year-old boys[23].
At rest, the arterial oxygen saturation was normal in all subjects (≥90.0%), but the arterial oxygen partial pressure was somewhat low in one boy with moderate pulmonary hypertension and a small baffle defect (9.4 kPa) and in another boy with a large atrial septal defect (9.6 kPa). The arterial oxygen partial pressure and saturation fell from rest to maximum exercise in all subjects (P < 0.0001). At peak exercise, 10/17 had an arterial oxygen partial pressure below 10.0 kPa, among whom five also had an arterial oxygen saturation of <90%. There was no difference in arterial oxygenation between subjects with the coronary sinus draining into the arterial atrium (n=7) or the venous atrium (n=10) (P > 0.73).

**Cardiac output**

The cardiac index rose from 3.3 l.min⁻¹.m⁻² at rest to 6.6 l.min⁻¹.m⁻² at peak exercise. In 11/15 subjects, the cardiac output per oxygen uptake was within 2 SD or normal data[24,26–28], but the group data were inferior to normal data as presented in Fig. 2 (P < 0.0001). The normal data in boys were obtained exclusively using the dye-dilution technique[26–28] and two of the studies were by one of the authors of this paper[27,28]. From Formula (2) it is evident that the low cardiac output per oxygen uptake in the study group implies that the arteriovenous oxygen difference was high compared with normal data and, consequently, also that the mixed venous oxygen content at maximal exercise was low in several cases, even though venous blood sampling was not performed. In fact, in 6/12 subjects, more than 90% of the available oxygen was consumed at peak exercise, as calculated from the arterial oxygen content and arteriovenous oxygen difference.

The stroke volume index fell from 50 ml.m⁻² at rest to 39 ml.m⁻² at peak exercise (P < 0.0001). In 13/15 subjects, there was a gradually falling stroke volume at higher heart rates (Fig. 3) and the stroke volume index was significantly correlated to exercise heart rate (r = −0.53, P < 0.0001). Only one subject demonstrated a considerable rise in stroke volume from rest to exercise, but in this boy stroke volumes also fell concomitant to higher heart rates (Fig. 3). None of the seven cases with a stroke volume at peak exercise below 80% of the resting value had systemic ventricle dysfunction at rest. At peak exercise, oxygen uptake per weight was significantly correlated to cardiac index (r = 0.61, P < 0.05) but not to stroke volume index (r = 0.41, P = 0.14).
Figure 2  Cardiac output at exercise after atrial redirection for complete transposition, n=15. Dotted lines represents means for normal boys 8–14 years old[26–28] and for children and adults as compiled by Cerretelli and Prampero[24].

Figure 3  Stroke volume index at exercise after atrial redirection for complete tranposition, n=15.
Blood pressure

The mean arterial blood pressure rose from 88 mmHg at rest to 98 mmHg at peak exercise. The total systemic resistance index (mean blood pressure/cardiac index) fell from 28-0 U x m² at rest to 15-7 U x m² at maximum work, the value at maximum being somewhat higher than the 11-3 U x m² recorded in healthy boys[27].

Discussion

Representativeness of data

The subjects in this study were a subset of an epidemiologically based population from which long-term survival data, postoperative status, and maximal exercise capacity have been previously reported[7,8,10]. An attempt was made to include all the survivors in the study, but due to the somewhat demanding study protocol, younger patients and patients with considerable sequelae had to be excluded. Nevertheless, in terms of exercise capacity, the subjects were representative of the mother population[10]. Since the survival rate in the mother population was low[7] and most of the participants had postoperative sequelae, one could argue that the exercise data reflect poor results of surgery and that the investigation therefore is not representative of these patient groups. However, Bink-Boelkens et al[29] has shown that, using proper investigations, a normal haemodynamic and electrophysiological status after Mustard’s operation is indeed uncommon. A recent comparative study in post-Mustard and post-Senning patients[30] and exercise data in post-Senning patients[5] have also confirmed that the long-term consequences of the Mustard and the Senning operations are similar.

Methodological considerations

More than half the study population had atrial baffle gaps. An atrial shunt may introduce an error in the calculation of pulmonary gas exchange and cardiac output.

During exercise, the pressure in the small venous atrium in these patients is likely to be right-to-left[1]. In right-to-left shunts, there is an early peak on the dye-dilution curve[31]. Since this peak was included in the curve-area calculation, the resulting cardiac output reflects the output of the systemic ventricle. Right-to-left shunts may nevertheless violate the assumption that alveolar carbon dioxide partial pressure (PACO₂) is equal to arterial carbon dioxide partial pressure[15,16]. However, since the dissociation curve for carbon dioxide in blood is rather steep[32], a small right-to-left shunt does not change the arterial carbon dioxide partial pressure considerably. Only in one case in this study was there a considerable shunt at rest. This subject was omitted from these analyses. In four additional subjects, we diagnosed a >5% right-to-left shunt during exercise and, in these cases, we cannot exclude the possibility that some data for cardiac output and pulmonary gas exchange might involve a small additional error.

Significance of data

We corroborated some previous exercise data of low oxygen uptake[1-5], low maximally achieved heart rate[1,3,5], abnormal stroke volume response[2,33] and high total peripheral resistance as a result of the low exercise cardiac output[2]. We also found a high prevalence for subnormal arterial oxygenation during exercise which could be due either to extrapulmonary right-to-left shunts or to an abnormal pulmonary gas exchange.

Source of low exercise oxygen uptake and cardiac output

The maximal oxygen uptake correlated with the cardiac index but not with the stroke volume index. Consequently, the low exercise capacity seems to be caused by a combination of an abnormal stroke volume response and a decreased maximal heart rate.

Since none of the patients with systemic ventricle dysfunction were among those with the poorest stroke volume response to exercise, factors other than systemic ventricle function may contribute to the falling stroke volumes. From Fig. 3 it is evident that the stroke volume seems to be heart-rate dependant. This lends support to the hypothesis that small atria and poor atrial function, with subsequent inadequate filling of the ventricles at higher heart rates, are important contributors to the abnormal stroke volume response[10] and that the chronotropic incompetence may, at least in part, be an adaptive mechanism to maintain adequate ventricular filling at higher heart rates[10]. In patients with pulmonary hypertension, the inability to properly increase pulmonary blood flow during exercise may also contribute.

Source of abnormal exercise arterial oxygenation

Although half the study population had atrial baffle gaps it seems unlikely that atrial shunts were responsible for all cases of falling arterial oxygen levels as well as the highly abnormal alveolar–arterial oxygen pressure differences during exercise. Excluding extrapulmonary shunts, the alveolar–arterial oxygen pressure difference is ascribed to ventilation–perfusion inequality, intrapulmonary shunts or diffusion limitation for oxygen between the alveoli and the pulmonary capillaries[25]. The presence of ventilation–perfusion inequality is probable in these patients. Asymmetrical distribution of
pulmonary blood flow in transposition has been demonstrated\textsuperscript{[34]}. Furthermore, we diagnosed a high prevalence of lung function abnormalities in these subjects, most notably among those with considerable pulmonary hypertension\textsuperscript{[9]}. Moreover, another study on atrial redirection for transposition found a high prevalence of reduced lung compliance\textsuperscript{[35]}. These lung function disturbances may not be clinically important at rest, but they may alter the ventilation–perfusion distribution during exercise\textsuperscript{[25]}. Additionally, although no patient had pulmonary venous obstruction, in a few of these patients, the pulmonary venous channel may be somewhat narrow, leading to increased pulmonary venous pressure during exercise, which may contribute to the abnormal gas exchange\textsuperscript{[25,36]}

In the presence of a high arteriovenous oxygen difference and a subsequent low mixed venous oxygen content during exercise, as there was in this study, even a low degree of ventilation–perfusion mismatch may increase the alveolar–arterial oxygen pressure difference considerably\textsuperscript{[21,25]} and consequently also lower the arterial oxygen tension.

An experimental study in pigs has demonstrated that an inappropriate cardiac output decreases mixed venous and arterial oxygen tension\textsuperscript{[57]}, further suggesting that the low cardiac output response plays a role in the low exercise arterial oxygenation in these patients. In athletes with a high cardiac output during exercise, diffusion limitation may contribute considerably to a high alveolar–arterial oxygen pressure difference, as the red blood cell transit time through the pulmonary capillaries becomes very short\textsuperscript{[38]}. This is unlikely in the study group as there was a low cardiac output which should render sufficient time for oxygen diffusion.

This study illustrates the highly abnormal exercise physiology in patients after atrial redirection for complete transposition and further emphasizes the palliative nature of these operations. Medium-term data indicate that the arterial switch may offer a far better alternative, not only in terms of anatomical results but also in terms of exercise physiology\textsuperscript{[39]}.

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