Transposition of Great Arteries Is Associated With Increased Carotid Artery Stiffness

Beatrix Mersich, Peter Studinger, Zsuzsanna Lenard, Krisztina Kadar, Mark Kollai

Abstract—Transposition of great arteries is the consequence of abnormal aorticopulmonary septation. Animal embryonic data indicate that septation and elastogenesis are related events, but human and clinical data are not available. We tested the hypothesis that large artery elastic function was impaired in patients with transposition of great arteries. We studied 34 patients aged 9 to 19 years, 12±3 years after atrial switch operation; 14 patients aged 7 to 9 years, 8±1 years after arterial switch operation; and 108 healthy control subjects matched for age. Carotid artery diastolic diameter and pulsatile distension were determined by echo wall-tracking; carotid blood pressure was measured by tonometry. Systolic pressure was higher and diastolic pressure was lower in patients than in controls. Patients with atrial and arterial switch repair were compared with their respective controls by 2-factor ANOVA. For patients with atrial switch repair versus control, stiffness index β was 4.9±1.5 versus 3.1±1.0 (P<0.001); for patients with arterial switch versus control, stiffness index β was 3.8±1.1 versus 2.1±0.6 (P<0.001). Similar differences were observed for carotid compliance, distensibility, and incremental elastic modulus as well. The interaction term was not significant for any of the elastic variables, indicating that carotid stiffening was a characteristic of the condition and not the consequence of different hemodynamics. Carotid artery is markedly stiffer in patients, suggesting that impaired elastogenesis may constitute part of the congenital abnormality. Since carotid artery stiffness has been established as an independent cardiovascular risk factor, this condition may have consequences in the clinical management of these patients. (Hypertension. 2006;47:1197-1202.)

Key Words: carotid arteries ■ arteries ■ elasticity

Transposition of great arteries (TGA) is a severe congenital heart defect in which the aorta arises from the right ventricle and the pulmonary artery from the left ventricle. TGA is the consequence of abnormal aorticopulmonary septal development. In animal models it has been demonstrated that large vessel elastogenesis was related to aorticopulmonary septation. Neural crest cells in the avian embryo, which form the septum, also synthesize the elastogenic matrix of the large vessel wall. We hypothesized that elastogenesis and aorticopulmonary septation were related events in human subjects as well; therefore, we compared the elastic parameters of the common carotid artery, a representative of large elastic arteries, in TGA patients and in age-matched control subjects to investigate whether impairment of large artery elastic function constituted part of congenital abnormality.

Materials and Methods

Subjects
Forty-eight TGA patients (34 male, aged 7 to 19 years) were recruited from the Gottsegen Cardiology Institute, Budapest, Hungary. Thirty-four of them (24 male, aged 9 to 19 years) had an atrial switch (AT-S) operation (Senning procedure), which was performed between the ages 6 months to 3 years; average time after repair was 12±3 years. The AT-S operation creates a tunnel between the atria, redirecting oxygen-rich blood to the right ventricle and aorta and the oxygen-poor blood to the left ventricle and pulmonary artery. Fourteen TGA patients (13 male, aged 7 to 9 years) had arterial switch (AR-S) operation, which was performed in the first lifetime of these patients; average time after repair was 8±1 years. In the AR-S operation the aorta and pulmonary artery are switched back to their normal positions. The AT-S and AR-S are hemodynamically very different operations, with the first putting a severe load on the right ventricle, which can undergo muscle failure, and the other essentially correcting the anomaly. Consequently, the prognosis for AR-S patients is more favorable as compared with that for AT-S patients. Surgical data were obtained from operative notes. All patients were in clinical status Class I as defined according to the New York Heart Association functional classifications. None of the children was taking any medications. Exclusion criteria included permanent pacing, atrial fibrillation or >2 ectopic beats per minute during data acquisition, clinical instability within the preceding 2 months, hypertension, and diabetes mellitus. One hundred-eight age- and gender-matched healthy control subjects were also studied. All subjects gave written informed consent to participate in the study, which was approved by the Ethical Committee of the Semmelweis University, Budapest, Hungary.

Carotid Ultrasonography
Diameter of the left common carotid artery, its pulsatile distension, and the intima-media thickness (IMT) of the posterior wall were measured with ultrasonography. The scanner was positioned 1.5-cm proximal to the bifurcation. The ultrasound device consisted of a

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vessel wall echo-tracking system (Wall Track System, Pie Medical, Maastricht, The Netherlands) combined with a conventional ultrasound scanner (Scanner 200 Pie Medical, Maastricht, The Netherlands) and has been described in detail before. Carotid artery diameter was recorded in 5 to 7 epochs, each containing 5 to 8 distension pulses.

**Carotid Artery Pulse Pressure**

Carotid artery pressure was measured by applanation tonometry (SPT-301, Millar Instruments, Houston, Tex), and the carotid pulse wave recording was calibrated by using diastolic and mean brachial pressure values measured by sphygmomanometry on the right brachial artery. Diastolic brachial pressure was assigned to the minimum value of the carotid pressure wave and the mean pressure to its electrically averaged value. This calibration of the tonometric signal was based on the assumption that mean pressure did not change in large conduit arteries and that diastolic pressure was not substantially different between the brachial and carotid arteries.

The carotid tonometric pressure was used to calculate carotid artery elastic parameters. The cut-off frequencies of the recording devices were above 25 kHz, therefore, no distortion was induced into the frequency content of pulsatile signals. 

**Carotid Artery Elastic Variables**

Carotid compliance was calculated as \( \Delta D / \Delta P \), where \( \Delta D \) is the change in diameter from end diastole to peak systole, and \( \Delta P \) is carotid pulse pressure. The distensibility coefficient (DC) was calculated as \( 2 \times \Delta D / (D \times \Delta P) \), where \( D \) is end-diastolic diameter. Stiffness index \( \beta \) was expressed as \( \ln(SBP/DBP) / \Delta(\Delta D) \), where \( SP \) and \( DP \) are systolic and diastolic carotid pressure, respectively. Carotid artery lumen cross-sectional area (LCSA) and intima-media cross-sectional area (IMCSA) were calculated as \( LCSA = \pi \times (D/2)^2 \) and \( IMCSA = \pi \times (D/2 + 1.5)^2 - \pi \times (D/2)^2 \). Incremental elastic modulus was determined as \( E = \frac{3 \times [1 + LCSA/IMCSA]]}{\Delta C} \).

**ECG and Respiration**

ECG was recorded continuously from the limb lead with the largest R wave. Respiration was recorded with an inductive system (RespirTrace System, Ambulatory Monitoring Inc).

**Ventricular Volumes and Ejection Fraction**

Ventricular volumes and ejection fraction of AT-S patients were determined by cardiac MRI (CMRI), which involved a standardized protocol that results in a series of short-axis cine loops covering the left ventricle (LV) and right ventricle (RV) from the atrioventricular valve plane to the apex. All studies were performed on a General Electric 1.5T Infinity MR instrument, equipped with EchoSpeed AC/CG gradients running Signa LX 9.1. An ECG-triggered gradient echo steady-state free precession cine sequence (FIESTA, time of repetition 3.0 to 3.5 ms, echotime 1.0 to 1.2 ms, flip angle 45 to 60 degrees) was used to acquire images in the short axis plane in contiguous 8-mm locations from the valve plane to the apex of the heart. The resulting data were distributed along s cardiac cycle to reconstruct 20 cardiac phases at each location. The images were transferred to an independent computer workstation (Sun Ultra 60, 512Mb RAM, dual UltraSpire, Solaris, Advantage Workstation 4.0) for data analysis. By use of visual inspection of the cine loops, the endocardial borders of the LV and RV were outlined at each phase of the cardiac cycle at all levels from base to apex. All borders were marked by the same observer. LV volumes and ejection fractions of AR-S patients were determined by transthoracic 2-dimensional echocardiography, using conventional techniques.

**Protocol**

Subjects were studied in the early morning under standardized conditions, in a quiet room at a comfortable temperature. All fasted at least 2 hours before testing and were asked to refrain from strenuous exercise or drinking alcohol or caffeine-containing beverages for 24 hours before the study. On arrival at the investigation unit, the subjects were equipped with measurement devices, and then rested in supine position for \( \sim \)15 minutes until the absence of evident heart rate and mean blood pressure trends demonstrated that satisfactory baseline conditions had been achieved. Carotid artery tonometric pressure on one side and diameter and wall thickness on the other side were recorded simultaneously, and these recordings were used to determine carotid elastic parameters. When recording sites were reversed, corresponding data from the opposite sides were not significantly different. Using the Bland–Altman analysis for paired data obtained from 34 TGA patients, the mean paired difference and the limit of agreement for stiffness index \( \beta \) was \(-0.02\) and \(-0.52\) to \(+0.46\), respectively. CMRI and echocardiography was performed on the same week in the morning hours.

**Data Analysis**

Data are expressed as mean±SD. Differences in variables between patients (AT-S and AR-S) and respective controls were analyzed by 2-factor ANOVA and the Tukey post hoc test. We selected control subjects, matched for age and sex, for each patient. Age ranges for AT-S and AR-S patients did not overlap, as AT-S subjects were older than AR-S subjects who were younger than 9 years old. We used a 2-factor ANOVA design, where one factor was condition (control versus TGA) and the other was type of operation (AT-S versus AR-S), which coincided with the age factor (older versus younger than aged 9 years). Relations between variables were investigated by univariate correlation analyses. Independent predictors of carotid artery elastic parameters were determined by multiple stepwise regression analyses. Significance was accepted at \( P<0.05\). Statistical analysis was performed by the SigmaStat for Windows Version 2.03 (SPSS Inc) program package.

**Results**

Patients with different types of operation (AR-S versus AT-S) were evaluated separately. Clinical characteristics of patients and controls are given in Table 1. Patients had lower body mass index. Systolic pressure was higher (although not significantly different from respective control at \( ^P<0.001; \quad ^P<0.001 \))

**Table 1. Clinical Characteristics of TGA Patients and Control Subjects**

<table>
<thead>
<tr>
<th>Clinical Data</th>
<th>AT-S (&lt;9 years)</th>
<th>AR-S (&lt;9 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patients</td>
<td>Controls</td>
</tr>
<tr>
<td>n, male</td>
<td>34 (24)</td>
<td>34 (24)</td>
</tr>
<tr>
<td>Age, y</td>
<td>13.2±2.9</td>
<td>13.3±3.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>154±17</td>
<td>160±14</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>45±15†</td>
<td>53±12</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>18.1±3.0†</td>
<td>20.3±1.6</td>
</tr>
<tr>
<td>SBP, mm Hg</td>
<td>115±9†</td>
<td>109±19</td>
</tr>
<tr>
<td>DBP, mm Hg</td>
<td>62±7†</td>
<td>70±8</td>
</tr>
<tr>
<td>MBP, mm Hg</td>
<td>80±7</td>
<td>82±8</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>81±11</td>
<td>79±14</td>
</tr>
</tbody>
</table>

**BMI indicates body mass index; SBP, systolic brachial pressure; DBP, diastolic brachial pressure; MBP, mean brachial pressure; HR, heart rate. Patients and controls were compared for differences by 2-factor (patients vs controls and AR-S vs AT-S) ANOVA. The interaction term was not significant for any of the variables; further comparisons were made within AR-S and AT-S groups using Tukey post-hoc tests. Data are given as mean±SD. Significantly different from respective control at \( ^*P<0.001; \quad ^P<0.01; \quad ^P<0.05. \)
significant in AR-S) and diastolic pressure was lower in patients, resulting in enhanced pulse pressure amplitude but no change in mean arterial pressure. In AT-S patients, LV and RV end-diastolic volumes were 66.8±21.1 mL/m² and 86.9±21.3 mL/m², respectively; LV and RV end-systolic volumes were 26.0±7.3 and 43.8±15.9 mL/m², respectively; and LV and RV ejection fractions were 60.1±6.2 and 50.1±7.1%, respectively, determined by CMRI. Values were normalized for body surface area. Ejection fractions were slightly lower as compared with reference values.12 In AR-S patients, LV volumes and ejection fractions, determined by echocardiography, were within normal limits.

Representative carotid artery distension and pressure pulse waveforms are illustrated in Figure 1; carotid artery dimensions and elastic parameters are summarized in Table 2. In the AT-S group, carotid artery end-diastolic diameter was smaller and pulsatile distension was less despite the higher pulse pressure. In the AR-S group, end-diastolic diameter was not different from control, and pulsatile distension was reduced relative to the much higher pulse pressure in AR-S than in controls. IMT was significantly larger in patients than in controls; however, this significance was lost when AT-S and AR-S controls were compared. This absence of correlation was not related to the type of operation. Consequently, in further analysis of the elastic variables, AT-S and AR-S patients were treated as 1 group.

From all control data, nomograms were constructed to age, which is an important variable determining arterial elasticity in health. In control subjects, compliance and DC of the carotid artery were related inversely, stiffness index \( \beta \) and \( E_{inc} \), were related directly to age (Figure 2). When patients' data were inserted into the nomograms, 15 of 48 patients had compliance and DC values below the lower 95% confidence limits of control data, and 21 and 14 patients had stiffness index \( \beta \) and \( E_{inc} \) values, respectively, higher than the upper 95% confidence limits of control data. In univariate analysis performed separately in patients and in controls, carotid artery elasticity parameters were associated with age, systolic and diastolic pressures, and heart rate, but were not related to time after repair, right or left ventricular dimensions, and

| Table 2. Carotid Artery Pressure, Dimensions, and Elastic Variables of TGA Patients and Control Subjects |
|---------------------------------------------------|----------|----------|----------|
| Carotid Variables | AT-S (>9 years) | AR-S (<9 years) |
| \( \Delta P \), mm Hg | 47±11* | 36±9 | 46±10* | 27±6 |
| D, \( \mu m \) | 5670±425† | 5986±544 | 5505±376 | 5670±556 |
| \( \Delta D \), \( \mu m \) | 679±144* | 851±159 | 892±155 | 820±116 |
| IMT, mm | 546±66 | 486±55 | 521±49 | 507±60 |
| Compliance, \( \mu m/mm Hg \) | 15.3±4.9* | 25.5±8.1 | 19.5±2.9* | 31.9±6.3 |
| DC, \( 10^{-3} \) mm Hg | 5.5±2.0* | 8.6±2.8 | 7.1±1.1* | 11.7±2.2 |
| Stiffness index \( \beta \) | 4.9±1.5* | 3.1±1.0 | 3.8±0.7* | 2.1±0.6 |
| \( E_{inc} \), mm Hg | 2.1±0.8* | 1.5±0.5 | 1.5±0.3† | 0.9±0.2 |

\( D \) indicates end-diastolic diameter; IMT, intima-media wall thickness; \( E_{inc} \), incremental elastic modulus. Patients and controls were compared for differences by 2-factor (patients vs controls and AR-S vs AT-S) ANOVA. The interaction term was not significant for any of the variables; further comparisons were made within AR-S and AT-S groups using Tukey post-hoc tests. Data are given as mean±SD. Significantly different from respective control at *\( P<0.001 \); †\( P<0.01 \).

![Figure 1. Representative waveforms of carotid artery distension and pressure pulses in a control subject and in a TGA patient with AT-S operation.](http://hyper.ahajournals.org/)

![Figure 2. Nomogram to age of carotid artery elastic parameters for control data (△), with patients data (○) inserted. Solid lines indicate the actual regression line for control data; dashed lines designate the 95% confidence limits. In control subjects compliance and distensibility coefficient (DC) were inversely \( r=-0.45 \) and \( -0.50 \), respectively, and \( P<0.001 \) related to age; whereas stiffness index \( \beta \) and incremental elastic modulus (\( E_{inc} \)) were directly \( r=0.55 \) and \( 0.56 \), respectively, and \( P<0.001 \) related to age.](http://hyper.ahajournals.org/)


**Elastic Parameters**  

**TABLE 4. Independent Predictors of Carotid Artery Elastic Parameters**

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Compliance</th>
<th>DC</th>
<th>Stiffness Index $\beta$</th>
<th>$E_{\text{inc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGA patients</td>
<td>3.30†</td>
<td>1.16†</td>
<td>$-0.85^*$</td>
<td>$-0.27^†$</td>
</tr>
<tr>
<td>Age</td>
<td>$-0.49^*$</td>
<td>$-0.15^*$</td>
<td>$0.12^*$</td>
<td>$0.08^*$</td>
</tr>
<tr>
<td>SBP</td>
<td>$-0.43^*$</td>
<td>$-0.58^*$</td>
<td>$0.05^*$</td>
<td>$0.03^*$</td>
</tr>
<tr>
<td>DBP</td>
<td>$0.45^*$</td>
<td>$0.15^*$</td>
<td>$-0.07^*$</td>
<td>$-0.20^*$</td>
</tr>
<tr>
<td>HR</td>
<td>$-0.12^*$</td>
<td>$-0.03^†$</td>
<td>$0.02^†$</td>
<td>$0.01^*$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.67</td>
<td>0.69</td>
<td>0.62</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Coefficient values for multiple forward stepwise regression analysis of the relations between carotid artery compliance, distensibility coefficient (DC), stiffness index $\beta$, and incremental elastic modulus ($E_{\text{inc}}$) on one hand and TGA status, age, systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR) on the other. $R^2$ indicates cumulative explained variance.

$^*P<0.001$; $^†P<0.01$; $^‡P<0.05$.  


ejection fractions in patient group (Table 3). Independent predictors of carotid artery elastic parameters were determined in multivariate regression analysis in all subjects. The strongest independent predictor proved to be TGA status, but age, systolic and diastolic pressure, and heart rate also explained additional variances (Table 4). No gender differences were found in the elastic variables neither in the patient nor in the control group.

**Discussion**

We compared carotid artery elasticity parameters in TGA patients and in age-matched healthy control subjects and found that all elastic variables indicated significant stiffening of the carotid artery in the patient group.

To our best knowledge, this is the first study in which arterial stiffness was studied in patients with congenital heart disease. We studied patients with transposition of great arteries and hypothesized that, in addition to disordered development of the aorticopulmonary septum, arterial elastic function was also abnormal. This assumption was based on embryonic data.1,2,14–18 The neural crest in the embryo is connected to the systemic circulation,3 the pulsatile load on the left ventricle is much higher than that on the right ventricle.

Since in TGA patients with AT-S repair the right ventricle is larger to start with, and our present data indicate that it is further increased by the additional power that is needed to distend the stiffer central arteries, RV ejection fractions in our patients was $50.1 \pm 7.1\%$, which is lower than normal control values reported in the literature.
ture. This reduction in right ventricular performance might be partly explained by the increase in pulsatile load.

We found no correlation between AT-S patients’ carotid artery stiffness and RV ejection fractions. This might be attributed to the relatively low number of patients and the low scatter of elastic data. It is also possible, however, that the impaired right ventricular function was also the result of abnormal myocardial development, which was not directly related to large artery stiffness. After neural crest ablation in the embryo, myocardial dysfunction developed and persisted throughout embryonic life. As for the mechanism underlying this myocardial dysfunction, depressed L-type calcium current, exhibition—contraction coupling, and calcium sensitivity of the contractile apparatus was found. No comparable data are available in human congenital heart disease.

**Perspectives**

Increased large artery stiffness is known to be an independent cardiovascular risk factor. Although consequence of this condition specifically in TGA patients is not known and further studies are needed to clear this issue, we speculate that our newly observed findings in TGA patients may indicate an increased attendance for healthy lifestyle in the clinical management of these children. Available evidence indicates that lifestyle modifications, particularly, aerobic exercise and sodium restriction, appear to be clinically efficacious therapeutic interventions for preventing and treating arterial stiffness. Although for most of TGA patients avoidance of strong physical activity is recommended, but regular sport activity may be advisable for them. In addition, other dietary modifications, like n-3 fatty acid (fish-containing) diet and refraining from active and passive smoking are important considerations.

**Limitations**

Since in AT-S patients the right ventricle may undergo muscle failure, it was of primary concern to determine right ventricular volumes and ejection fraction in this group of patients. For that purpose CMRI was used, because echocardiography is not considered as a reliable technique for quantitative determination of right ventricular function. On the other hand, CMRI is relatively expensive, and data evaluation is very time consuming. Therefore, in AR-S patients, where right ventricular function was of no particular concern, only left ventricular function was determined by conventional transthoracic echocardiography, as part of the routine diagnostic procedure. Because of the more regular and symmetric geometry of the LV, LV volumes and ejection fraction can be measured reliably by echocardiography. Although CMRI is thought to be a more precise method to determine ventricular volumes and ejection fractions, it is comparable to conventional 2-dimensional echocardiography. This difference in used methodology, however, is considered as a limitation.

Because of the cross-sectional design of the study, we could not examine the direct influence of surgical procedures on arterial stiffness. Also, we were not able to establish whether carotid artery stiffening was the result of gradual postoperative derangement in vessel wall distensibility. Another limitation is the relatively low number of patients, although it represents all of the patients who had been operated on in Hungary.

**Acknowledgments**

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**References**


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