Aus der Klinik für Herz- und thorakale Gefäßchirurgie

der Universität zu Lübeck

Direktor: Prof. Dr. med. H.-H. Sievers

Anatomic correction of transposition of the great arteries with a physiological, spiral anastomosis of the great vessels: Construction of a model and in-vitro results of the anastomoses

Inauguraldissertation

zur

Erlangung der Doktorwürde

der Universität zu Lübeck

-Aus der Sektion Medizin-

UNIVERSITÄT ZU LÜBECK

vorgelegt von

Léon M. Putman

aus Zoetermeer, Niederlande

Lübeck

2014

1. Berichterstatterin/Berichterstatter: Prof. Dr. H.-H. Sievers
2. Berichterstatterin/Berichterstatter: Prof. Dr. M. Reppel
Tag der mündlichen Prüfung: 9. Januar 2015
Zum Druck genehmigt. Lübeck, den 9. Januar 2015
Promotionskommission der Sektion Medizin

Table of contents

1. Introduction

1.1 Background

Transposition of the great arteries (TGA) is a congenital heart defect which occurs in approximately 20-30 per 100000 new births (1). This is approximately 2,2% of the total number of congenital heart disease. TGA is the second most common cyanotic heart disease, after Fallot's Tetralogy (1).

The causative defect is a malformation of the outflow tract resulting in a discordant ventriculo-arterial connection. This pathological configuration of the great vessels leads to a significant hemodynamic dysfunction with a catastrophic outcome if not treated.

In the physiological concordant situation there is a connection between right atrium, right ventricle and pulmonary artery and between left atrium, left ventricle and aorta. In the ventricular-arterial discordant situation such as occurs in TGA there is a connection between the right ventricle and the aorta and the left ventricle and the pulmonary artery.

This means that there is a separation between the pulmonary and systemic circulation. Non-oxygenated blood from the right atrium and right ventricle flows into the aorta and oxygenated pulmonary venous blood flows into the left atrium, left ventricle and again the pulmonary artery. Without a mixing of these two circulations, either through an open ductus Botalli, atrial septal defect or ventricular septal defect this condition is fatal after physiological closure of the open ductus Botalli within weeks to months leading to death in 96 % in patients after one year (2).

In 50-75% of the cases there is a so called simple TGA. In these cases there is either no further cardiac anomaly or only an open ductus Botalli, an atrial septal defect or hemodynamically irrelevant ventricular septal defect (3).

In the case of a complex TGA there is usually a ventricular septal defect with or without left ventricular outflow tract obstruction.

To treat this vascular abnormality the anatomic correction with retransposition of the great arteries seems to be the logical concept. Despite the simple looking repair method the results are still suboptimal. Therefore the search for an improved surgical technique is ongoing.

1.2 Anatomy and hemodynamics

This thesis concerns the simple TGA. In simple TGA there two atria and two ventricles in concordant arrangement. However in contrast to the normal anatomy (figure 1) the aorta arises from the right ventricle and the pulmonary artery from the left ventricle (figure 1).

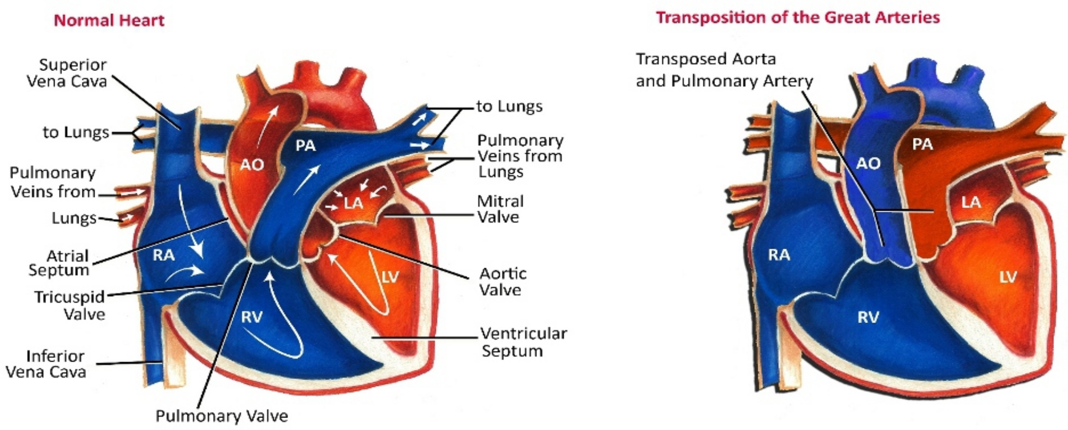

Figure 1: Schematic of a normal heart and a TGA heart, where the aorta arises from the right ventricle and the pulmonary artery from the left ventricle, the course of the great arteries is parallel and not spiral as in the physiologic condition. AO: aorta, LA: left atrium, LV: left ventricle, PA: pulmonary artery, RA: right atrium, RV: right ventricle (5).

The course of the great arteries is more parallel and not spiral as in the physiological anatomic connection. The spatial position of the aortic root in relation to the pulmonary root shows some kind of variation from the anterior-posterior to the side by side position (figure 2). In most cases the aortic root is in a 45° position anterior and to the right of the pulmonary root and called the classic form of TGA (figure 2).

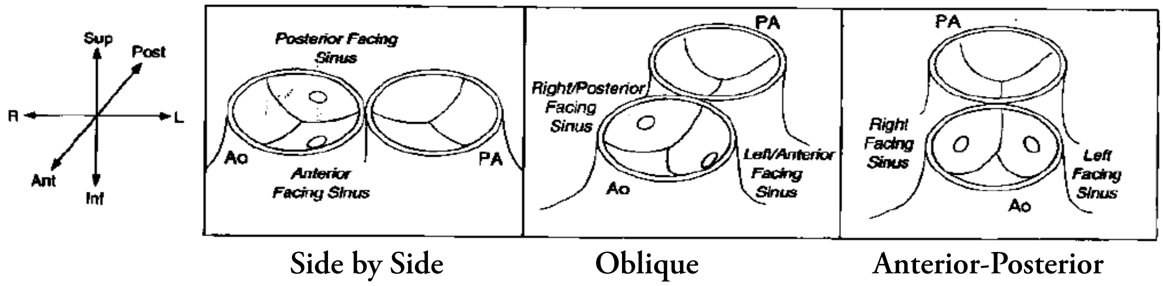

Figure 2: *Most common interrelationships of the great arteries (adapted from 4). The anterior-posterior position is the 0° and the oblique the 45° position in our study. The oblique or 45° position is the most frequent form.*

Furthermore the aortic root is located more cranially (roughly 1/2 of the root height) compared to the pulmonary root. This ventriculo-arterial discordant connection has hemodynamic consequences.

The systemic venous blood is gathering in the right atrium, flowing to the right ventricle and then ejected into the aorta and the systemic circulation. Thus non-oxygenated blood is circulating. The pulmonary circulation within TGA is as follows: pulmonary venous blood drains into the left atrium, the left ventricle and is ejected into the pulmonary trunk (figure 3). Both of these circulations are separated when the open ductus Botalli closes and no other connection between the circulations for blood-mixing is available, for instance an atrial or ventricular septal defect (figure 3).

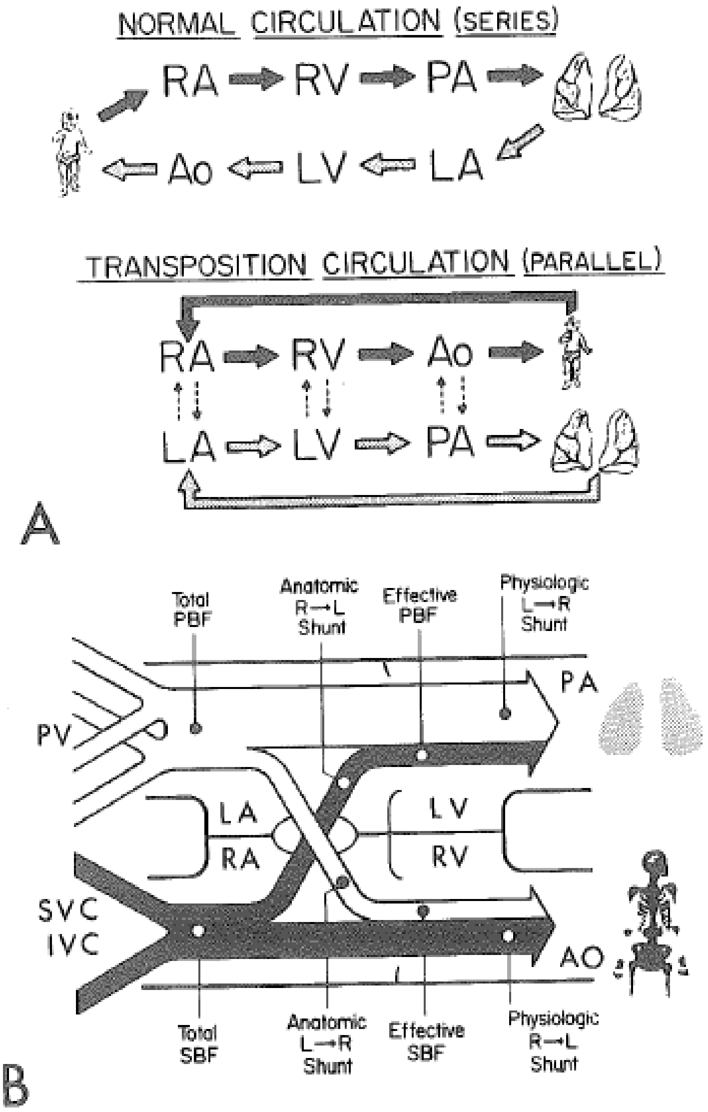

Figure 3: *The circulation in TGA. A: Systemic and pulmonary circulation pathways. B: Circulation scheme demonstrating flows and shunts in infants with TGA. AO: aorta, LA: left atrium, LV: left ventricle, PA: pulmonary artery, RA: right atrium, RV: right ventricle. SVC: superior vena cava, IVC: inferior vena cava, PV: pulmonary vein (adapted from 4)*

Figure 4 shows an intra-operative view on a TGA situs in its 'classical' form. Here it can be seen that the aortic root is located cranial and 45° anterior and to the right of the pulmonary root. The left coronary artery is shown in its anatomical position arising from the aortic root.

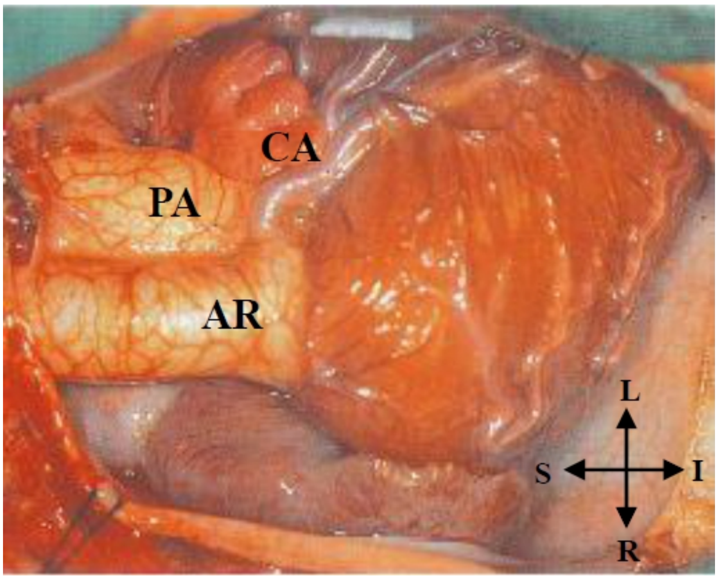

Figure 4: *Operative and schematic view of a TGA heart (6) CA: coronary artery, PA: pulmonary artery, AR: aortic root, L: left, R: right, I: inferior, S: superior.*

The coronary arteries in TGA present a complete spectrum, one of the most used method to classify them is the so-called Leiden classification (7). The coronary arteries in TGA are arising from the aortic root and thus carry non-oxygenated blood.

Both vessels have 3 sinus. The pulmonary trunk is considered a fixed position and the aorta 'circles' around it. 2 of the 3 aortic sinus are always directly on the pulmonary trunk. The non-facing sinus is the starting point, and the observer is put into this non-facing sinus and looks at the pulmonary trunk. The right-hand sinus is called number 1 and the left hand one is called 2. For both it is noted which coronary arteries are coming from a sinus. Figure 5 shows the 6 main variations (7).

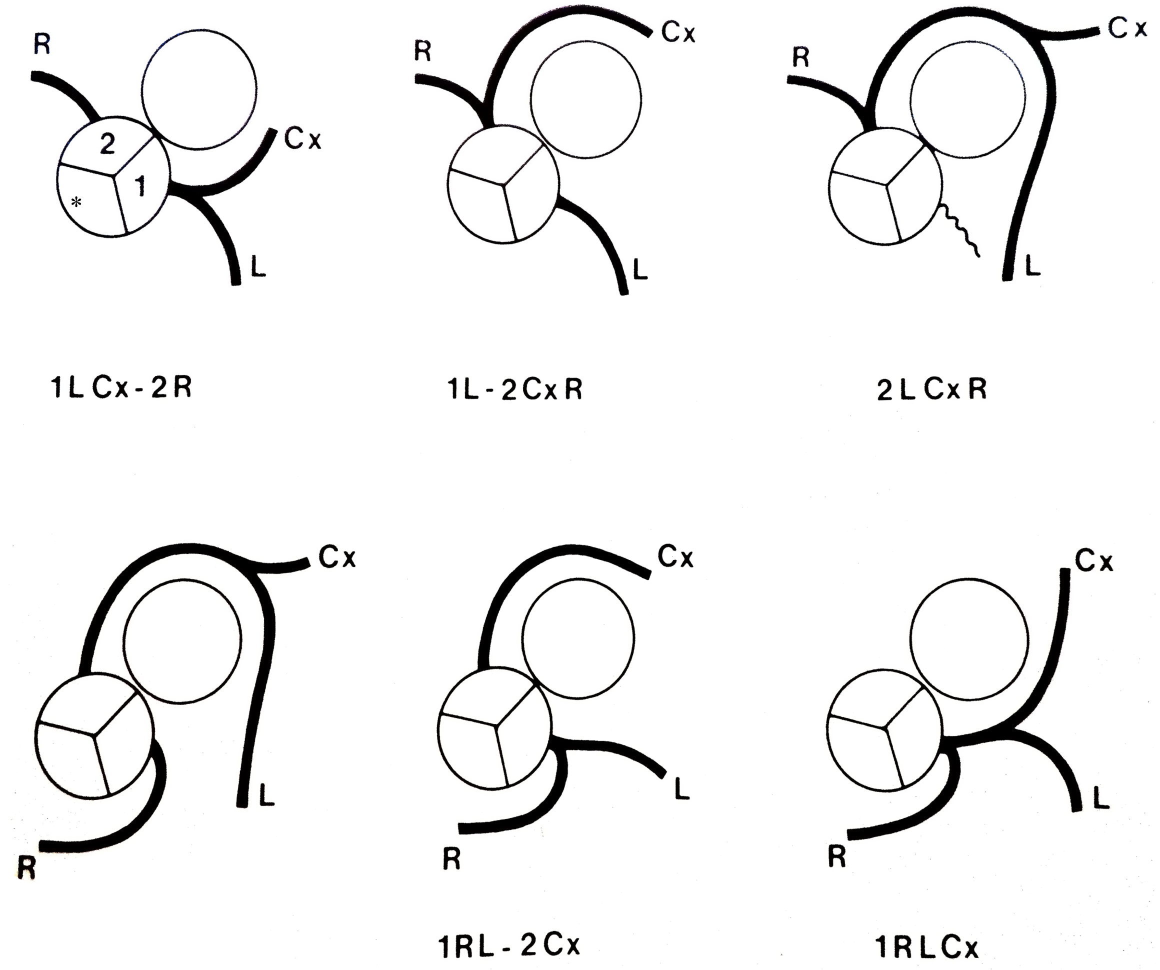

Figure 5: *The 6 main variations in coronary artery anatomy in TGA according to Gittenberger-de Groot. R: right coronary artery, L: left coronary artery, Cx: circumflex coronary artery, *: Position of the observer looking at the pulmonary root, 1: right hand sinus, 2: left hand sinus. (7)*

Figure 6 represents a schematic of TGA, the Lecompte technique and a spiral reconstruction.

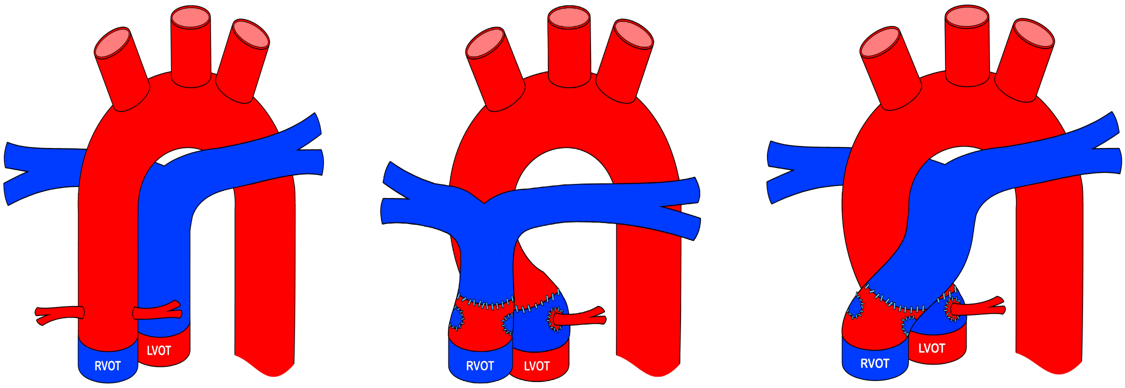

Figure 6: *Schematic drawings of TGA (left), principles of repair: Lecompte technique (middle) and spiral reconstruction (right) Red = aorta, Blue = pulmonary artery, RVOT = right ventricular outflow tract, LVOT = left ventricular outflow tract.*

1.3 Therapy

1.3.1 Historical view

Due to the separation of both circulations (pulmonary and systemic) after closure of the open ductus Botalli, TGA is fatal. Observation of survival due to mixing of blood, for instance in atrial or ventricular septal defect, led to the introduction of a surgical technique to create an atrial septal defect by Blalock and Hanlon in 1948 (8).

The Blalock-Hanlon atrio-septectomy required a thoracotomy. In 1966 a catheter-based technique to create an ASD, the Rashkind balloon atrio-septostomy was introduced (9).

Rashkind's technique is currently still used in the management of newborn with a TGA.

The idea that transposing the great arteries would be the treatment of TGA led to development of arterial switch techniques. The first surgical attempts by different groups in the 50's were all unsuccessful, mainly due to the difficulty of transposition the coronary arteries from the aortic root to the neo-aortic root, but also due to a failing left ventricle (10, 11).

After these failed attempts the surgical interest was shifted to a change in venous inflow, thus correcting the defect on the atrial level rather than the arterial level. This means a physiological repair, but not an anatomical correction with the right ventricle serving the systemic circulation lifelong (10, 11).

The atrial switch was introduced by Senning in 1959, using a complicated technique to switch the venous blood flow, with the use of the patients own atrial tissue (11).

Following Senning's technique Mustard introduced a technique to perform an atrial switch using pericardial tissue or Dacron prosthetic material (12, 13). This operation seemed less complex than the Senning procedure.

In the following decades mainly the Mustard procedure was performed (10).

Both the Mustard operation and the Senning procedure showed excellent short-term results, the long-term outcome caused some concern. This was related to the main problems such as arrhythmias and right ventricular (systemic ventricle) dysfunction. The cumulative survival was 95% at 5 years, 94% at 10 years, 93% at 15 years, 92% at 20 years and 91% at 25 years. Freedom from reintervention was 94% at 5 years, 89% at 10 years, 85% at 15 years and 76% at 25 years (14).

Failure of the right systemic ventricle often leads to reduced exercise capacity and finally heart transplantation.

In 1961 Idriss publishes his work on an Arterial Switch Operation (ASO). This technique entailed a switching of a segment of the aorta, including the coronary arteries onto the left ventricular outflow tract, and a spiral, anatomically correct switch of the great vessels. After multiple experiments in post-mortem patients the procedure was performed on 2 patients, both of them died. The first patient was 7 years of age at surgical correction with TGA, atrial septal defect and intact ventricular septum. The cause of death was acute left-ventricular failure, which at autopsy was due to a thin-muscled dilated left ventricle. This left ventricle was not able to sustain systemic pressure after 7 years of working 'only' for the low resistance pulmonary circulation. The second patient was 3,5 months of age. In this case, to promote circular growth of the anastomosis, the aortic suture was interrupted on multiple instances, this led despite attempts to reach haemostasis, to fatal bleeding (15).

The first successful ASO was performed in Brazil by Jatene in 1976, in a child with complex TGA with ventricular septal defect. The drawings of Jatene suggest a more or less anterior-posterior position of the great vessels before the operation and an anatomic correction with physiological spiral arrangement of the great arteries (16, figure 7).

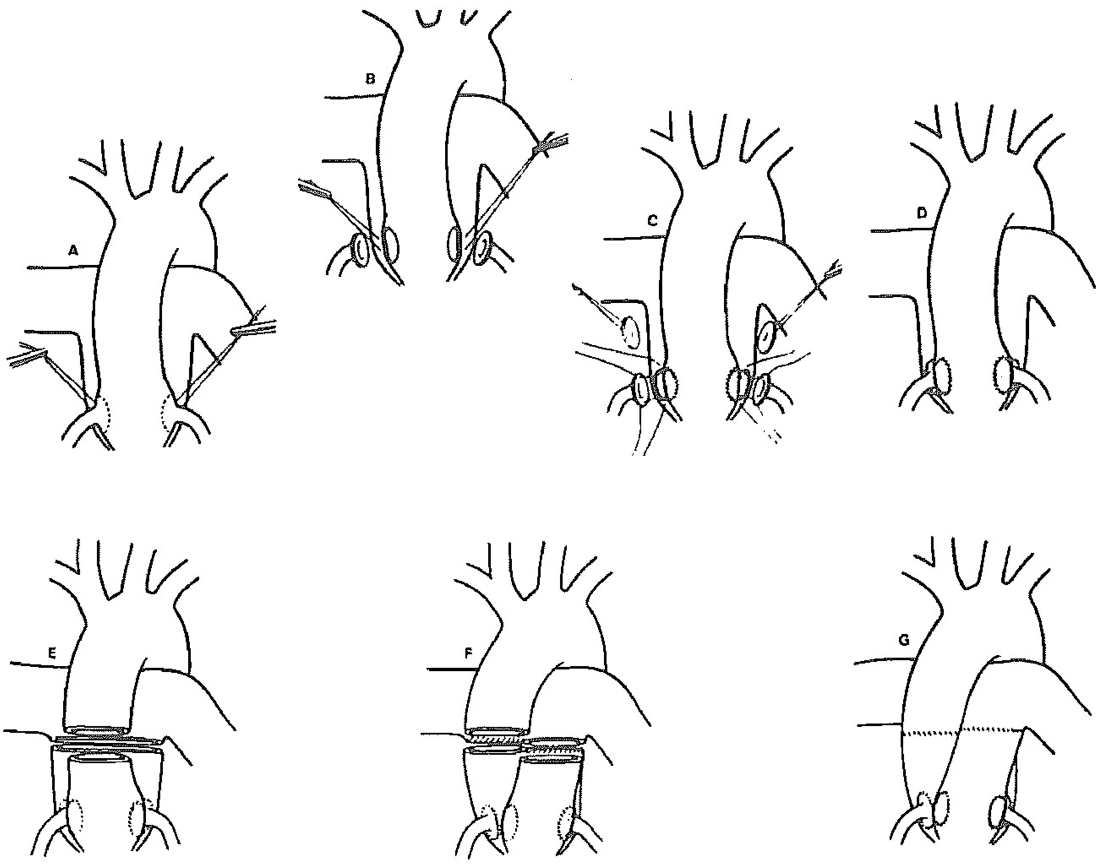

__Figure__ 7: The Jatene procedure. (A) marks the position of the aorta anterior to the pulmonary artery before the operation, (B) coronary buttons are removed and transposed into the neo-aortic root (C, D). Next the great vessels are transected and anatomically correct reconnected in a spiral arrangement (E, F, G) (16).

This operation was successful because the left ventricle was able to take over the systemic circulation due to a hemodynamic significant ventricular septal defect, which has posed the left ventricle on high pressure until the operation. However in the majority of patients with simple TGA this kind of operation was not possible due to the fact that the heart-lung machine technology allows only for performing operations in children of 3 to 4 years or older at those days. Therefore Yacoub developed a two-stage anatomic correction entailing a training of the left ventricle months before the later anatomic correction. This training operation was performed by banding of the pulmonary artery which causes sclerosis in this area, meaning that at the time of anatomic correction the pulmonary artery has to be replaced by prosthetic material. In some cases a stenosis developed in these conduits but only when the conduit was positioned to the right of the aorta and not to the left which would be the normal anatomic arrangement. As a consequence of the improvement in heart-lung machine technology it was possible at the end of the seventies and the beginning of the eighties to operate on babies and thus to perform the anatomic correction days after birth. A training of the left ventricle became superfluous because in the first weeks after birth the left ventricle is still able to sustain systemic pressure (17, 18). In 1984 Castaneda published a case-series where he performed the ASO in neonates, between 18 hours and 32 days of age at the time of surgery, with excellent results (3).

For this kind of operation the so called Lecompte technique was introduced and is until now the routine surgical technique for anatomic correction of simple transposition of the great arteries (19). This technique entails however that the pulmonary bifurcation is transposed in front of the aorta (figure 8). The short-term clinical results have been reported to be excellent (21, 22, 23), however long-term follow-up revealed some concerns including ascending aorta dilatation (23), sometimes progressive aortic regurgitation (24), suspected to be related to a malposition of the aorta (25), and pulmonary artery stenosis especially at the site of the pulmonary artery branches riding on the aorta (19).

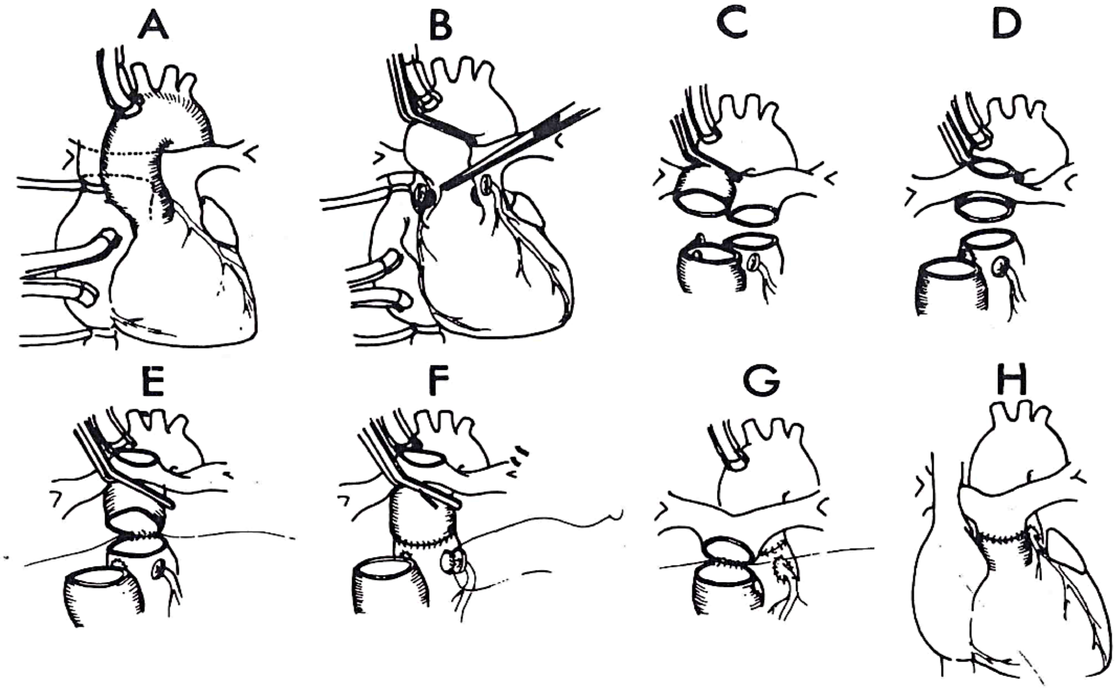

Figure 8: The Lecompte technique in ASO. After transection of the aorta and pulmonary trunk the pulmonary trunk is transposed anterior to the aorta (D) and both great vessels are anastomosed (E, F, G, H) (19)

1.3.2 Current status of surgical therapy

The currently most applied technique to correct simple TGA is the ASO with the Lecompte technique (1) (figure 8).

Long-term follow-up is described from several groups. For instance Fricke et al. describes early mortality of 2,8%, risk factors were: weight under 2,5 kg and complex TGA. Late-mortality was 0,9% after mean follow-up of 10,6 years. Reintervention rate was 5.9% after 15 years (26). Similar results are shown by Pretre (20).

Results from Wernovsky and colleagues reported on a mortality rate of less than 5% and a reintervention rate of less than 10%. Long-term survival is 91% at 8-years (27). Pulmonary artery stenosis and coronary obstruction are main reasons for surgical reintervention, additionally moderate to severe aortic valve insufficiency may develop after ASO.

Lange shows progression of aortic valve insufficiency over time, however the number of reoperations was low. Close follow-up was considered necessary to observe the need for interventions on the valve (28).

Choi showed long-term results concerning the aortic valve, pulmonary stenosis and coronary obstruction. Freedom from significant aortic insufficiency at 20 years was 78%, freedom for pulmonary stenosis was 68% and freedom from coronary obstruction was 96%. Most of the patients develop and grow normally, but close follow-up was again advised for follow-up of aforementioned potential problems (29). Figure 9 shows an example of pulmonary stenosis after the Lecompte technique on a 3D reconstruction of a magnetic resonance angiography.

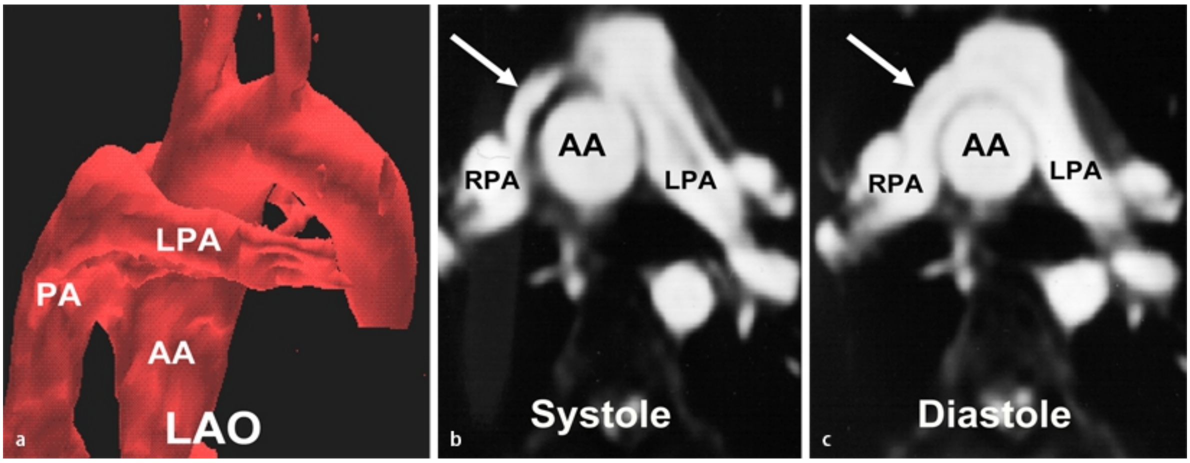

Figure 9: *3D-Reconstruction of Magnetic Resonance Angiography. Typical position, with the pulmonary branches (LPA, RPA) 'straddling' the aorta (AA). A systolic (b) and diastolic (c) image show a temporary dynamic stenosis of the RPA by the expansion of the aorta. LAO 'left anterior oblique' (32).*

Agnoletti et al. demonstrates that the angle in the thoracic aorta, as occurs after the

Lecompte technique, in the long-term promotes root dilatation, aortic valve insufficiency and early pulse-wave deflection. He suggests new surgical techniques to correct TGA without Lecompte (25).

Sievers et al. reported, in 2012, on excellent results with physiological, spiral anatomic correction in simple transposition in 5 cases being performed 20 years before. As far as we know that was the first successful primary anatomic correction performing a normal spiral shaped retranspositioning of the great vessels in simple transposition of the great arteries with excellent long-term results (30).

These promising results renewed interest in physiological spiral correction to overcome the potential negative aspects of the Lecompte technique.

In Taiwan, Chui et al use a spiral correction, in which the pulmonary artery is partially wrapped around the neo-aorta, and share a common wall so that an arterial switch can be performed without Lecompte (31). However this technique is complicated, not completely physiological and long-term results are missing.

1.4 Aim and research question

This thesis has the goal to design and construct a model and to investigate the surgical techniques applied to correct simple TGA in a spiral physiological connection of the great arteries during ASO, considering the different spatial arrangements of the great vessels in an in-vitro model. The principle of both the surgical techniques, the Lecompte and the spiral anastomosis, are shown in figure 6.

The intention was to create a final configuration of the anastomosis without undue tension, torsion or kinking. Surgical variables were: extent of mobilisation of the pulmonary artery and the aortic arch, the transection height of the great arteries and lastly a patch enlargement of the pulmonary artery anastomosis.

2. Methods

2.1 Measurement of anatomic dimensions relevant for model foundation

For the in-vitro studies a model was constructed. This model should allow for arranging the great vessels in the different spatial positions from 0° to 45°, the most frequent arrangements thereby simulating real dimensions of the great vessels. Therefore a literature review was performed to assess the different anatomic positions of TGA as depicted in figure 2. Next the diameter and length of the aorta and pulmonary artery were measured from 7 pre-operative cardiac catheterisation angiograms from the University Hospital of Schleswig-Holstein, Campus Kiel, Department of Pediatric Cardiology. The films were assessed using a Tagarno 35AX (Tagarno AS, Horsens, Denmark). All angiocardiograms include a reference sphere of 30 mm, filmed at cardiac level to obtain the scale of each patient. Length of the aorta was defined as the distance between annulus of the aortic valve and the take-off of the brachiocephalic trunk, the diameter of the ascending aorta was measured at the mid-aortic level. For the pulmonary artery the length was defined as distance from the annulus of the pulmonary valve to the bifurcation and the diameter was determined at the mid-pulmonary level. The mean value from 7 measured diameters was taken. Only the systolic diameters were taken because it was sometimes difficult to obtain correct diastolic data.

2.2 Production of the great arteries with latex

Using the above measurements a backing-clay model was constructed for aorta and pulmonary artery. Care was taken to simulate the physiological, spatial relationship in addition to the diameter and length. Especially the more caudal position of the pulmonary root in relation to the aortic root was considered.

The next step was to apply liquid latex (Latex Emulsion, Glorex, Switzerland) to the models to simulate the great vessels out of latex material. After sufficient drying several layers of latex were applied to acquire a sufficient thickness. The latex vessels were taken of the clay via a longitudinal incision which was glued afterwards with latex. The thickness of the latex vessels was adjusted to simulate by and large physiological conditions as measured by the stress strain relationship. A Zwick-Roell Z2.5 (Zwick GmbH & Co. KG, Ulm, Germany) device was used for obtaining the stress-strain curves. Since the physiological compliance of the great vessels is around 10% and the diameter of the great arteries around 10 to 15mm a strain of up to 1,5 mm was considered equivalent.

2.3 Construction of an assembling model for the great arteries

The latex vessels had to be fixated on a special grid as to simulate the human spatial relationships of the great vessels. Care was taken to construct an assembling model to simulate the mobilization of the great vessels during surgery. Therefore the 'supra-aortic' vessels and 'pulmonary branches' are held by clamps, these clamps have spherical joints which enable to arrange the vessels in all directions. Due to these joints the great vessels can freely be changed in their position, simulating the surgical situation after mobilisation of the pulmonary branches into the hilus and the mobilisation of the ascending aorta, aortic arch and the supra-aortic vessels.

The samples were filled with ultrasound transmission gel (Aquasonic, Parker Laboratories, Fairfield USA) up to 40mmHg to distend the latex vessels in order to detect tension and torsion thus simulating quasi-physiological conditions.

To simulate the various anatomic positions in TGA (figure 10), the 'left-ventricle' rod was fixed within the metal base. Both 'right-ventricular' and 'descending aorta' rods are movable and placed on a heavy magnet to allow free adjustment to obtain the required spherical relationship of the great vessels After choosing the right positions the rods can be fixed, so that the position is further stabile. This way the aortic root can be changed freely to simulate anterior-posterior position and oblique positions. Both these moveable rods are also adjustable in height, so that the aortic root can be positioned to the pulmonary root to get as close to the anatomic situation as possible (see chapter 1.2).

2.4 Study protocol

The most frequent occurring positions of the great vessels were chosen, that is 0°, 20°, 35° and 45° positions of the aortic root rightward and anterior to the pulmonary root (figure 10). The latex vessels were arranged to this protocol on the assembling model.

Next the height of transection of both vessels was chosen and the great arteries transected.

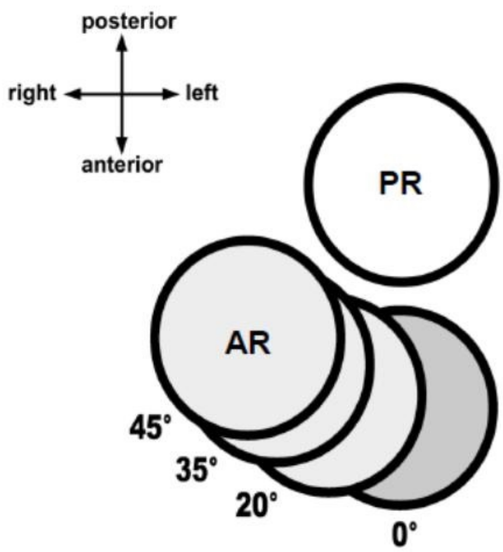

Figure 10: *The different spatial relationships of the great arteries tested in this study. The view is from cranial to caudal. (PR, pulmonary root, AR: aortic root) The AR is positioned 0°, 20°, 35° and 45° in relation to the PR.*

First the distal aorta is anastomosed to the neo-aortic root, after that the distal pulmonary artery is connected to the neo-pulmonary root. All anastomosis are performed with 7-0 polypropylene sutures in a running fashion and the sutures glued (UHU plus 300, UHU GmbH & Co KG, Bühl, Germany). Thereafter the vessels were filled with ultrasound gel.

Special care was taken to find out if the connection between the distal pulmonary artery and the former aortic, now neo-pulmonary root can be performed without tension or torsion in relation to the different spatial positions of the aortic root. If this was not possible 'mobilisation' of the pulmonary branches and aortic arch was intensified, the transection level optimised and patch enlargement performed with differently shaped patches, circular ring or wedges. Then the vessels were pressurised with gel allowing for evaluating the situs in a quasi-physiological status.

3. Results

3.1 Dimension of the great arteries

Table 1 presents the pre-operative measurements of aorta and pulmonary artery, derived from cinecardiograms.

	Vessel	Mean (in mm)	minimum	maximum
Length	Aorta	32,9	29,7	35,8
	PA	22,4	20,7	24,1
Diameter	Aorta	11,1	8,6	13,6
	PA	12,5	11,4	13,7

Table 1: Cinecardiography derived mean values of great vessel dimensions.

The ascending aorta has a greater length than the pulmonary artery whereas the diameter was comparable between both great vessels. These data were used for producing the clay and latex models.

3.2 Great vessels in latex

Figure 11 shows the clay models, closely resembling the configuration of TGA. The sinus of Valsalva delineating the aorta and pulmonary roots are also simulated.

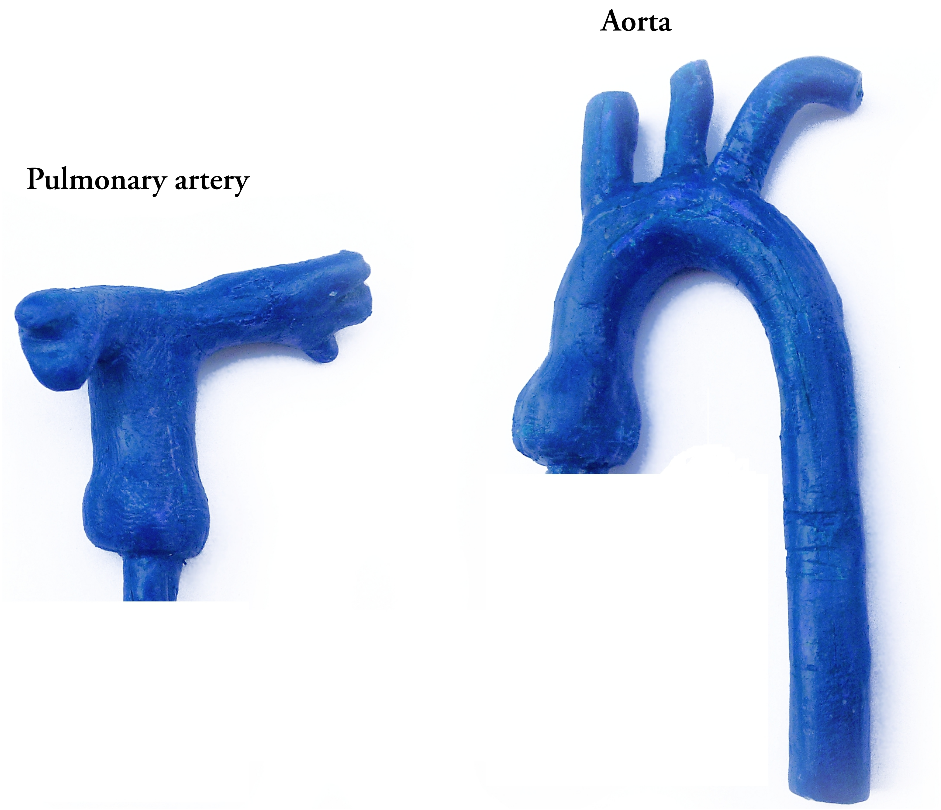

Figure 11: *The clay models that were used to produce the vessels.*

Thereafter latex models were constructed on the basis of these clay models. As an example for the latex vessels, aortic root and aortic arch with descending is shown in figure 12.

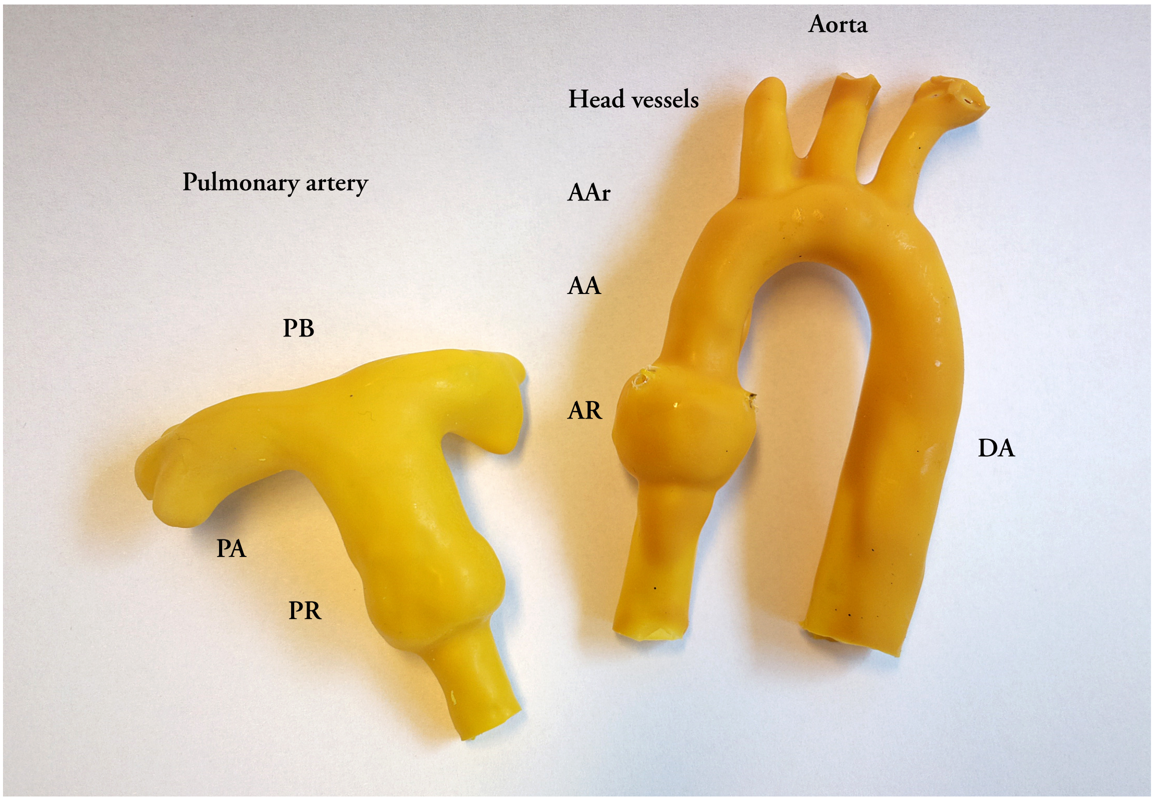

Figure 12: An example for the latex vessels. Left: pulmonary root, artery and bifurcation. Right: The aortic root, ascending aorta, arch, head vessels and descending aorta. AR: aortic root, AA: ascending aorta, AAR: aortic arch, DA: descending aorta. PR: pulmonary root, PA: pulmonary artery and PB: pulmonary bifurcation.

Figure 13 shows the stress-strain measurements performed on a porcine aorta and the latex vessel, showing that the latex material has compliance characteristics roughly simulating physiological conditions.

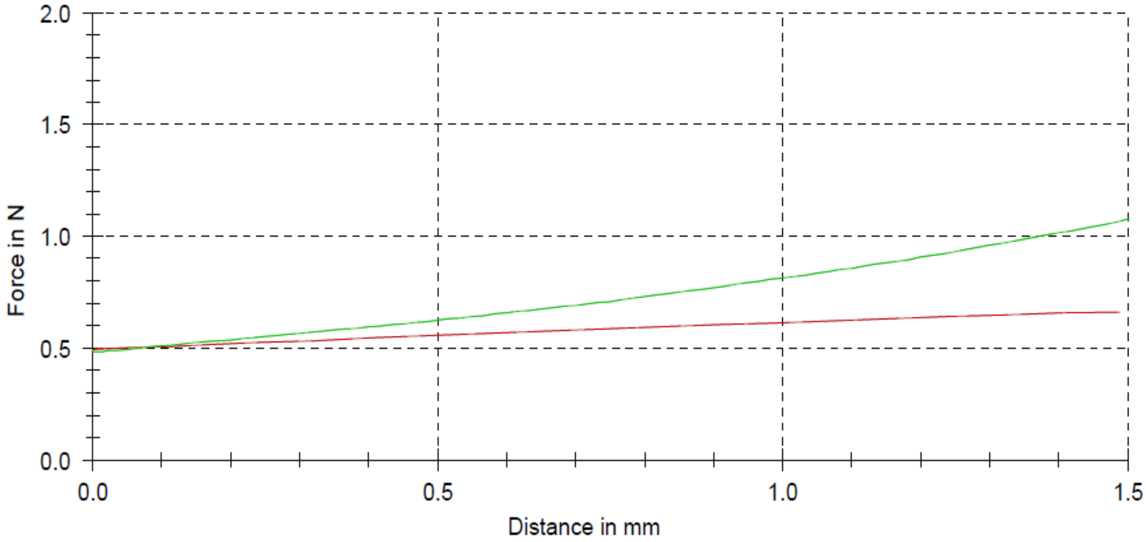

Figure 13: *Stress strain measurements. Porcine aorta (green) & latex (red)*

3.3 Assembling model for the great arteries

Figure 14 shows the assembling model for fixation of the great arteries. This model is made of steel. It is possible to change the height due to a screw mechanism on the 'left ventricular' rod. Both 'ascending aortic' and 'descending aortic' rods can be moved freely and have a heavy magnet so that it is fixed afterwards. Various clamps on moveable ball-bearings are available to fix the distal vessels (supra-aortic and pulmonary branches)

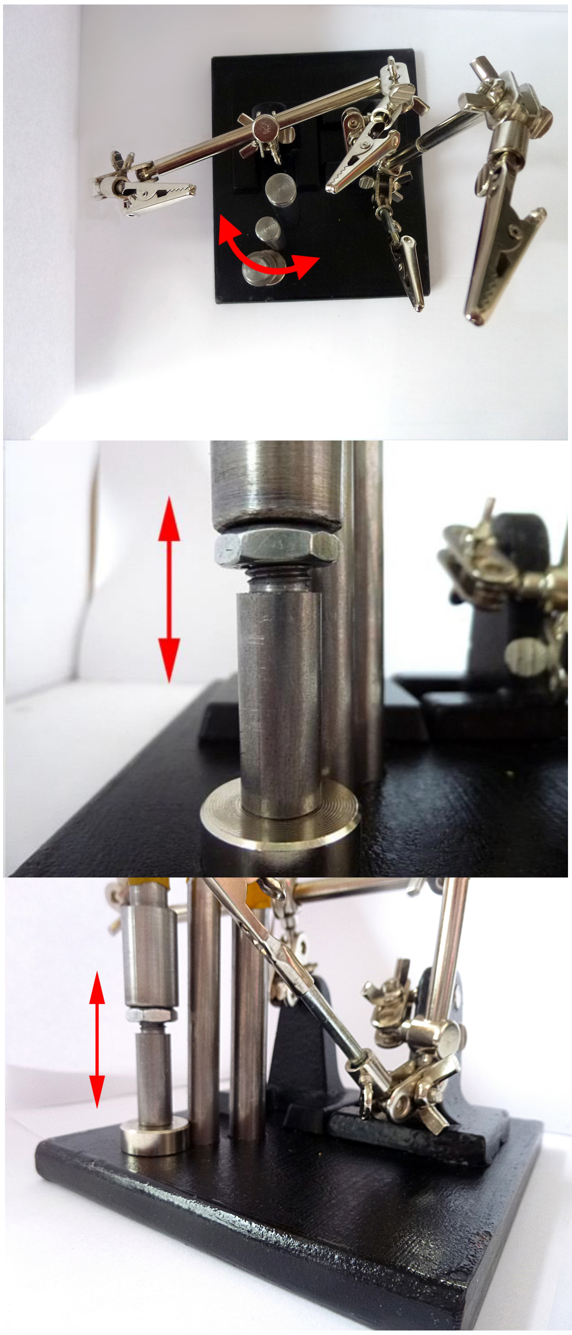

Figure 14: *Assembling model for fixation of the great arteries. Top: View from cranial on the model. The arrow depicts the moveable aortic rod, upward are the clamps depicted for fixation of the pulmonary arteries and head vessels. Middle: The screw mechanism to adjust for height of the aortic rod is shown. Bottom: The model is shown from the left side depicting the aorta, the pulmonary and the descending aortic rods.*

Figure 15 demonstrates the complete model with the latex vessels, the metal rods for fixing the great vessels, the clamps for correct adjustment of the great arteries in the chosen spatial arrangement. This figure also shows that the pulmonary root is positioned more caudal than the aortic root.

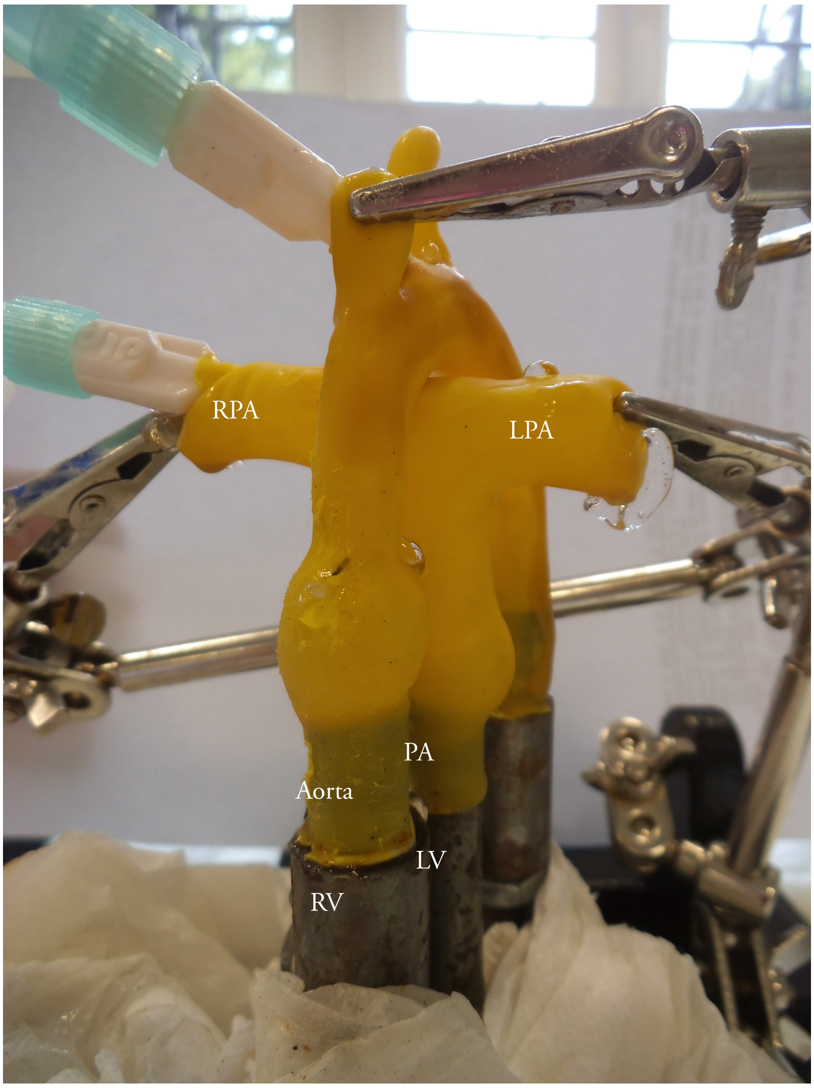

Figure 15: *The complete model with gel filled vessels. Two cannula are used to inject the gel into the vessels. The aorta is anterior to the pulmonary artery. (RV=right ventricle, LV=left ventricle, PA= pulmonary artery, LPA=left pulmonary artery, RPA=right pulmonary artery).*

3.4 Models of surgical anastomosis

3.4.1 The Lecompte technique

Figure 16 shows the model of TGA, the transection area, the transposition of the pulmonary bifurcation in front of the aorta and the final result clearly demonstrating the straddling of the pulmonary bifurcation on the aorta. In figure 17 the Lecompte model is pressurized demonstrating the steep angle of the ascending aorta and the riding of the pulmonary bifurcation on the ascending aorta.

This example shows that the in-vitro model simulates adequately the clinical situation.

Figure 16: *Lecompte technique. Upper left shows the starting anatomy from anterior. A 45° angle between aorta and pulmonary artery is used. Upper right shows the transection of both vessels at the same height just above the sino-tubular junction. Lower left shows the position of both vessels after Lecompte and lower right shows the post-correction situation. Straddling of the pulmonary artery on the aorta is noted (white arrow), the kinking in the pulmonary artery is artificial.*

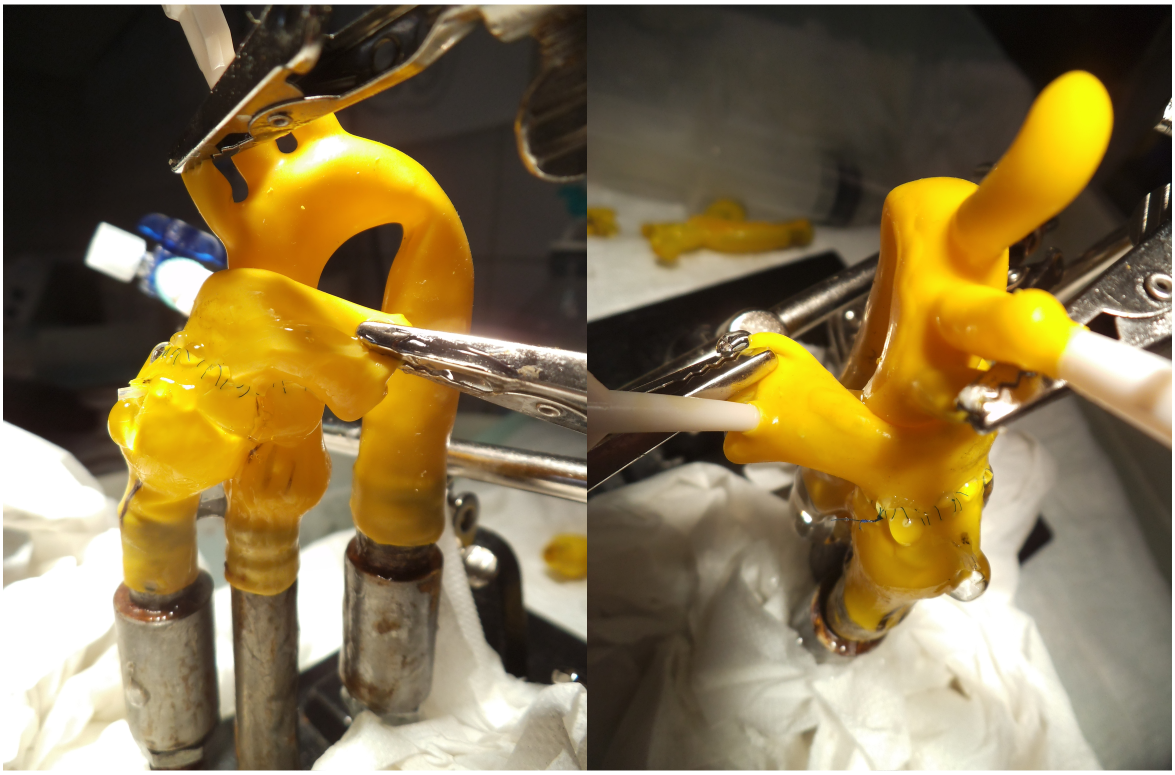

Figure 17: Lecompte model filled with gel, noted is the straddling of pulmonary artery on the aorta and acute angulation of the aorta. This model adequately simulates the clinical situation. Left is view from left lateral, right is view from cranial.

3.4.2 Spiral anastomoses

3.4.2.1 TGA in anterior-posterior (0°) position

The anterior-posterior position of the great arteries presents no problem for a tension and torsion free spiral anastomosis of the great vessels (figure 18). The model simulates adequately the physiological spiral arrangement of the great vessels.

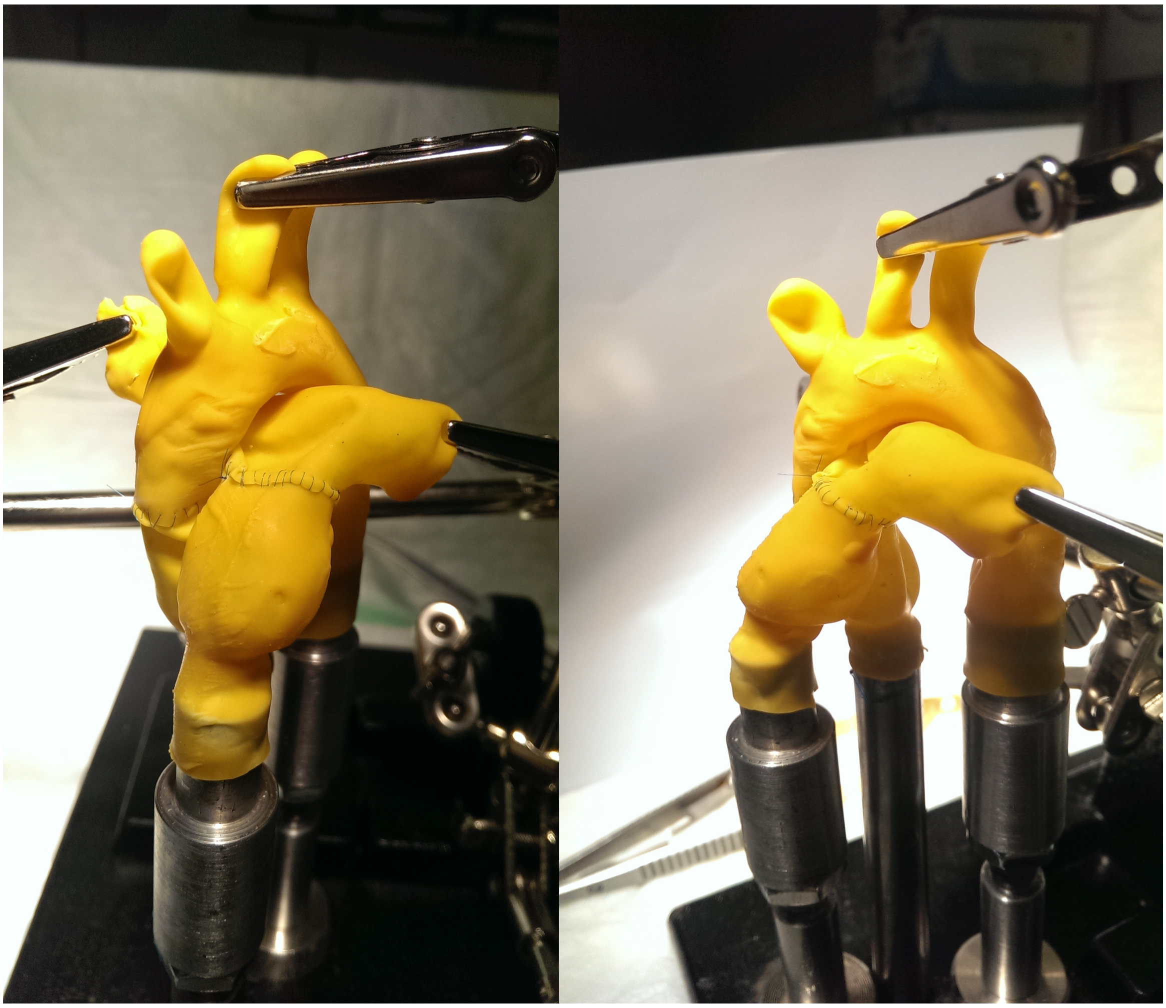

Figure 18: *Completed reconstruction of a physiological spiral connection of the great arteries, from a 0° anterior-posterior starting position. On the left the anterior view of the model after a spiral connection is shown, the anterior vessel is arising from the right-ventricle and is the neo-pulmonary artery, the posterior vessel is the aorta arising from the neo-aortic root. On the right the lateral view is presented. The suture lines are to be seen, the anastomosis can be performed without tension or torsion.*

3.4.2.2 TGA in 20° position

For the TGA in 20° position the same results can be obtained as in the 0° configuration of the great vessels (figure 19), however the transection of the aorta is performed more distally and the mobilisation of the pulmonary bifurcation and aortic arch has to be extended to gain length for a tension and torsion free anastomoses (table 2).

Figure 19: *Model after correction, from a 20° angle, showing a tension- and distortion-free anastomosis on both vessels. View from left lateral (left) and anterior (right).*

3.4.2.3 TGA in 35° position

Four experiments were performed in the 35° position of the great arteries as shown in figure 20. The anastomoses can be made without distorsion, albeit a little more tension on the pulmonary artery may occur.

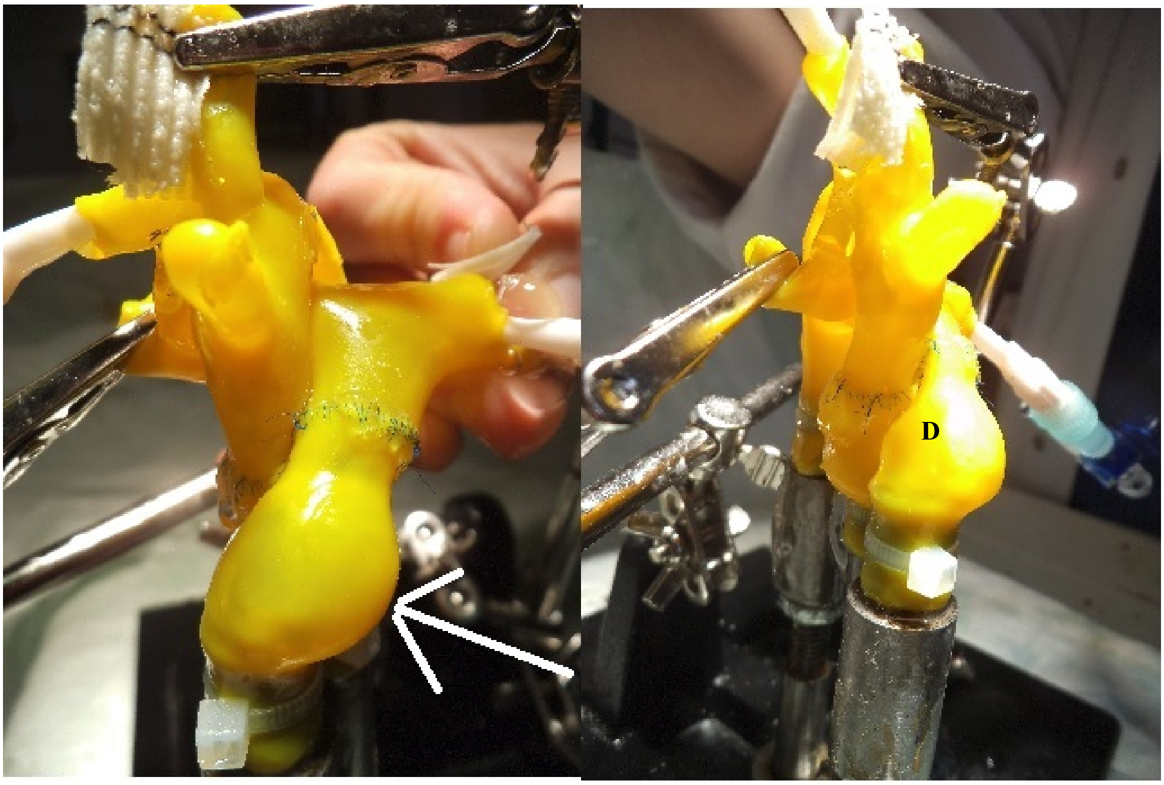

Figure 20: *The 35° model filled up with gel from an anterior (left) and a right lateral view (right). The pulmonary root (arrow) is slightly distended (D) but no area of significant tension or distortion can be observed.*

3.4.2.4 TGA in 45° position

In this arrangement of 45° position of the aortic root anterior and to the right of the pulmonary root a direct anastomosis of the pulmonary artery without undue tension was not possible. Although more 'mobilisation' of the pulmonary bifurcation and aortic arch was performed a patch plasty of the pulmonary artery was necessary to achieve a tension and torsion free anastomosis of the pulmonary artery in all 4 experiments performed with this 45° arrangement. In two cases the patch consisted of a circular segment of a same sized latex tube and in two cases the patch had the form of a wedge of such a circular segment (figure 21). The maximal width of these patches was 5 mm located at the convexity of the pulmonary artery.

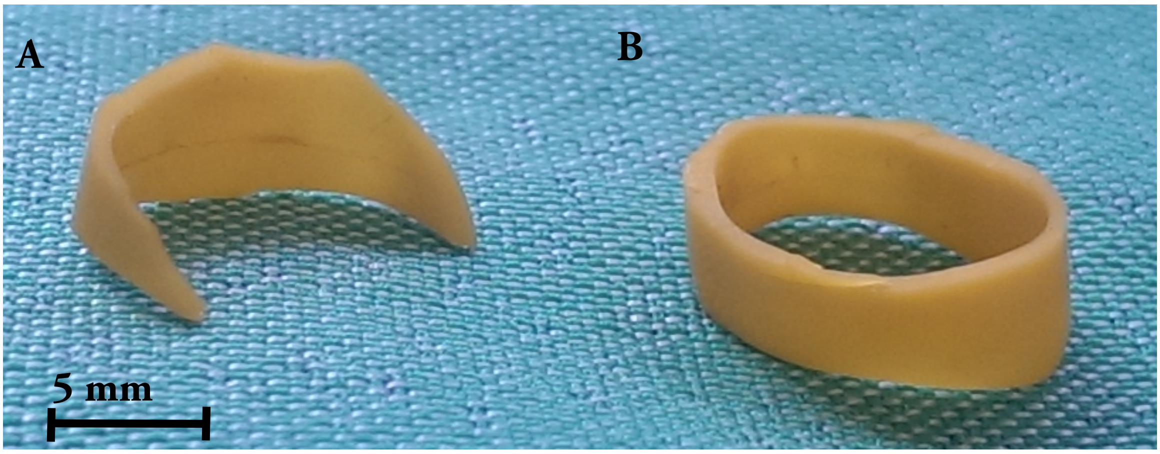

Figure 21: *The two different types of the patches to increase the length of the pulmonary artery are shown (A=wedge like patch, B=circular patch configuration).*

In figure 22 the different stages of these experiments are shown (anastomosis with tension and torsion, patch insertion and final configuration without tension and torsion of the great vessels)

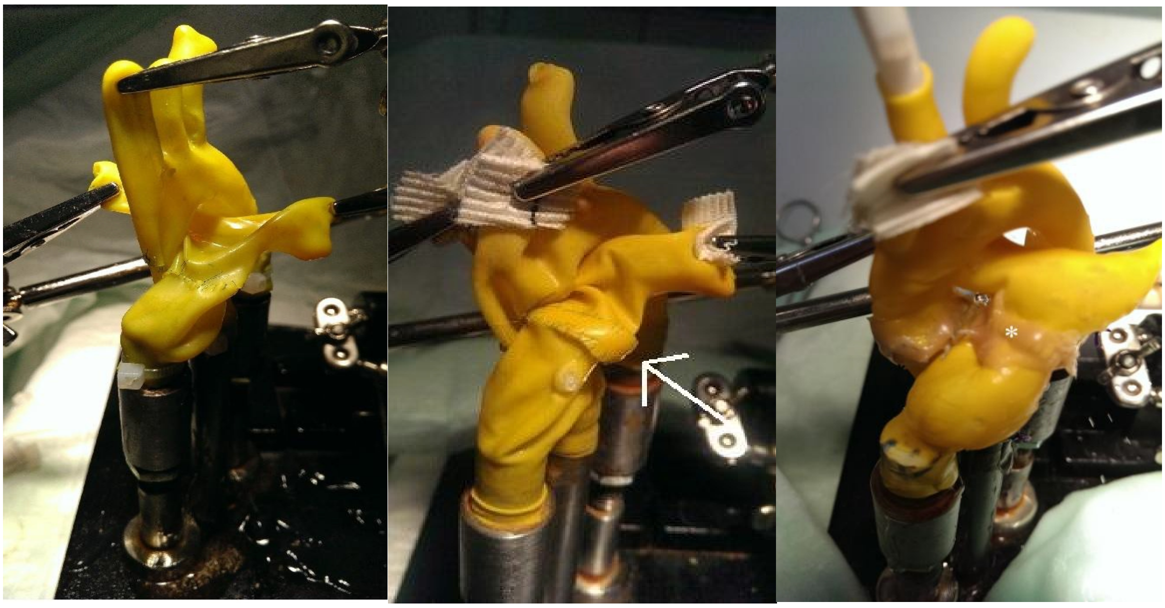

Figure 22: *A model at 45° angle. The left view shows the arrangement after anastomoses, with clear distortion and tension on both vessels. The middle view shows the status after insertion of a wedge formed patch(arrow). The right view demonstrates the anastomoses after pressurising with gel. There was no tension or torsion after the patch enlargement. The asterisk highlights the patch.*

3.5 Summary of results on the different anastomoses

			Transsection height					Mobilisation	
Attempt	Angle Ao/PA	Procedure	Aorta	PA	Fits wthout Material	Defect form	Defect size	Aorta	PAB
	0=AP, 90=S-b-S	spiral/Lecomp-te	above STJ, in mm	above STJ, in mm			in mm	in mm	in mm
1	0°	Spiral	5	8	Yes	-	-	4	3
2	0°	Spiral	5	6	Yes	-	-	4	3
3	0°	Spiral	5	4	Yes	-	-	4	3
4	0°	Spiral	5	6	Yes	-	-	4	3
5	20°	Spiral	8	8	Yes	-	-	6	4
6	20°	Spiral	8	6	No	Ring	4mm	4	3
7	20°	Spiral	8	6	Yes	-	-	8	4
8	20°	Spiral	8	6	Yes	-	-	5	5
9	35°	Spiral	8	8	Yes	-	-	6	4
10	35°	Spiral	6	8	Yes	-	-	6	4
11	35°	Spiral	8	8	Yes	-	-	6	4
12	35°	Spiral	8	8	Yes	-	-	6	4
13	45°	Spiral	8	5	No	Wedge	5mm	6	4
14	45°	Spiral	6	6	No	Ring	5mm	5	5
15	45°	Spiral	8 anterior, 5 posterior	5	No, tension high			6	4
16	45°	Spiral	8	5	No	Wedge	5mm	8	4
17	45°	Lecompte	8	8	Yes	-	-	4	4

Table 2: Results of different anastomoses: The starting angle is increased, the performed procedure is shown. The height of transection above the sino-tubular junction and the extent of 'mobilisation' of the distal great arteries are also presented. If there was no possibility to anastomose the pulmonary artery without tension and torsion the defect was filled with different patch plasties. 0° anterior posterior position, 20°, 35°, 45° means extent of rotation of the aortic root in relation to the pulmonary root.(Ao=Aorta, PA=Pulmonary artery, PAB=Pulmonary artery branches)

Table 2 presents data from the different performed procedures in accordance to the spatial relationship of the great arteries. What we observed was that an increased angle from anterior-posterior position to the classic 45° position required intensified ‘mobilisation’ of the distal great arteries, optimising the transection level and lastly patch enlargement which is logical since the distance between the neo-pulmonary root and the pulmonary bifurcation is increasing. Thereby the size of the patch seemed relatively small with sizes of 4 to 5 mm in width. Also the impact of mobilisation may be observed and the transection height, thus having more length for the reconstruction of the pulmonary artery. The more the distal arteries are mobilised the better it is possible to anastomose the pulmonary artery stumps without tension and torsion and additionally if the aorta is transected more cranially in comparison with the pulmonary artery the anastomosis is further facilitated. We could show that starting from an anterior-posterior 0° position the spiral physiological connection can be performed without difficulty as shown by several repeated experiments. Furthermore increasing laterality of the aortic root in comparison to the pulmonary root, especially to the 45° arrangement prevented direct anastomosis of the pulmonary artery if not a patch enlargement, albeit of small width, was performed.

4. Discussion

This in-vitro study shows that a physiological spiral anastomosis of the great arteries in patients with TGA is possible, especially in the spatial anterior-posterior (0°) position of the aorta in relation to the pulmonary artery and also up to 35° anterior and rightward position of the aortic root without additional material. The more the aortic root is rotated to the right (observed from cranial) the more difficult it is to perform a direct spiral anastomosis without tension or torsion. In these cases an extended 'dissection' of the pulmonary branches and the ascending aorta, aortic arch and head vessels is required to gain some length of the great vessels to perform a tensionless anastomosis. But not only a forced 'dissection' of the distal vessels, but also the height of the transection of the great arteries in relation to the sino-tubular junction of both vessels, the aorta and the pulmonary artery, can have a favourable effects on the quality of the anastomosis. We could show that transection more distally on the aorta and more proximally on the pulmonary artery provides some length to optimise the anastomosis.

However if these surgical manipulations ('dissection' and transection) are not adequate, some kind of patch plasty of the pulmonary artery is necessary, in some cases a small ring of latex was required, in others a semilunar shaped patch with the widest dimension of the patch at the convexity of the connection. The maximal width of these patches was albeit small with roughly 5 mm.

Materials with growth potential are desirable for these only few days old babies. One potential material is the autologous pericardium, pedicled if possible, to allow preservation of viability and thus probably growth. Arnaiz et al. could show that autologous pericardium as a patch for repair of supravalvular aortic stenosis appears to show no drawbacks on long-term follow-up (33). Furthermore autologous pericardium has previously been shown to have growth potential and has been used in vascular reconstruction (34). Both clinically and ex-vivo studies have shown the potential benefits of fresh pericardium, compared to glutaraldehyde fixed pericardium in terms of stiffness, strength and growth potential (35, 36).

In 1 case of the Sievers series (30) a strip of percardium was used, showing only a mild pulmonary artery stenosis (max 20 mmHg) when the patient was outgrown, 20 years after the physiological spiral switch operation. This type of patch plasty may also be integrated in the trouser shaped pericardial patch reconstruction sometimes used for closure of the defects in the pulmonary artery after excision of the coronary artery buttons.

The experience of Sievers (30) in 5 patients with a direct spiral anastomosis shows promising results at over 20 years follow-up both clinically and with 4D-Flow magnetic resonance tomography. A part of these data was presented in 2012 (30) (live recording available from http://jeronimo.dhzb.de/LangeSymp12/Sievers/ accessed on 1 July 2014) . This physiological spiral anastomosis showed a near normal flow distribution in the great arteries, whereas the Lecompte technique presented abnormal flow in both the aorta and the pulmonary branches. This was a small case series, however a renewed interest in this spiral connection was generated. Furthermore it was demonstrated by these magnetic resonance tomography images 20 years after the primary ASO that the pulmonary root appears to be migrated more towards to the left, thus to a more normal position. It remains speculative if this is some kind of rotation of the outflow tract within these young patients induced by mechanotransduction due to tension or if it is a flow phenomenon. The flow within the spirally reconstructed patients was more laminar and spiral as it is in normal controls. This is shown in figure 23 (30). In these cases with physiological spiral anastomosis there was no or only a mild pulmonary stenosis and mostly normal sized or slightly enlarged aortic roots. In this study we considered a spatial relationship of the great arteries from anterior-posterior (0°) to 45°

rotation of the aortic root. In some patients a further rotation to 90°, called side by side arrangement can be observed. It is imaginable that in these cases even more enlargement of the pulmonary artery is needed to perform a tension and torsion free anastomosis. May be that in these patients the Lecompte technique or a direct anastomosis with the pulmonary artery on the right side of the aorta is preferable. These situations need further investigation to find out the optimal solution.

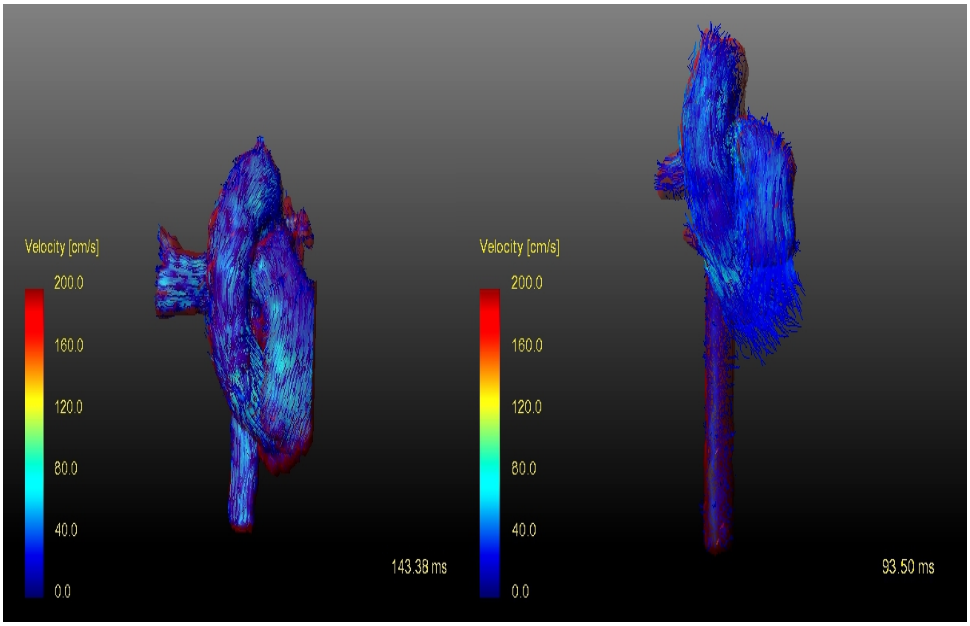

Figure 23: *4D-Flow MRT images, on the left a healthy control, on the right a spirally corrected TGA, 20 years after surgery showing almost normal conditions (30).*

In 1981 Lecompte reported on 9 patients receiving an arterial switch procedure without the use of prosthetic material, due to the anterior position of the pulmonary artery. This may lead to several problems, such as aortic root dilatation, aortic valve insufficiency and pulmonary branch stenosis (19, 21, 25, 26, 28, 30).

Several authors showed a decreased distensibility of the neo-aorta after ASO, possible reasons being surgical manipulations and sutures or vascular morphology, with the former pulmonary artery in a high-pressure circulation. Despite similar histology differences in the muscle-fiber distribution are reported (37, 38, 39).

These structural differences between aorta and pulmonary artery in TGA, compared to normal neonatal vessels were shown by Lalezari et al. (40). A de-differentiation of the smooth muscle tissue in the pulmonary artery and untreated sinus in TGA was found, which was not due to abnormal flow. This structural abnormality may be also a cause for neo-aortic root dilatation late after ASO (40).

Jhang shows the importance of the neo-aortic root geometry after ASO during re-implantation of the coronary-arteries. The so-called trapdoor technique with enlargement of the sino-tubular junction leads to aortic insufficiency on the long-term (41).

Chiu et al. have shown a modified procedure to restore a spiral flow, this however is a relatively complicated procedure, with the aorta and the pulmonary artery partially sharing a common wall leading a questionable physiologic situation (31).

If the spiral anastomosis can ameliorate these late complications of the Lecompte technique remains to be established by further longer follow-up studies. Furthermore the influence of the spiral anastomosis on the coronary arteries which are also transposed, need further evaluation.

Main limitation of our study is the in-vitro nature with non-compliant vascular models. A more accurate model is difficult to produce as animal studies within TGA models are unavailable. Furthermore porcine heart studies have shown different proportions of the great vessels, making these models difficult. We tried to construct the great vessels from latex material with roughly similar stress strain characteristics compared to normal and furthermore tried to simulate the dimensions of the spiral relationships of the great arteries as close as possible to the natural conditions.

A further limitation of this study is the non-pulsatile nature of the model. The models were only filled up with ultrasound gel to pressurise the vessels, no flow was induced. However it remains questionable if flow and pulsatility would have influenced the results. Only morphological characteristics were the focus of the study.

Also we did not consider the necessary transposition of the great arteries which could potentially influence the anastomosis. Thus the next step is to integrate coronary arteries into the model to evaluate the exact position of transposing the coronary arteries in the neo-aortic root, thereby preventing a kinking or torsion of the coronary arteries and also evaluate its influence on the spiral anastomosis.

In conclusion a physiological spiral anatomic correction is possible in TGA with a spatial arrangement of the great vessels from anterior-posterior (0°) to 35° rightward position of the aortic root. Surgical techniques such as extensive dissection and optimal transection height are favourable. In large rotation angles (45°, classical TGA) the use of patch material albeit of a small size may be necessary. Our in-vitro results may increase the knowledge in performing a spiral physiological anastomosis of the great vessels in ASO and underline the reconsideration of this technique, hopefully to reduce the potentially unfavourable long-term results of the Lecompte technique.

5. Summary

The anatomic correction of TGA originally was performed as a spiral retransposition of the great arteries, however was successful in some cases only with complex TGA and ventricular septal defect. For simple TGA the Lecompte technique was later introduced which puts the pulmonary artery in front of the aorta. This technique has shown some unfavourable results in the longer term follow-up.

The aim of the current study was to investigate in an in-vitro model the anatomic correction of simple TGA using a spiral physiological postoperative anastomosis of the great arteries for different spatial positions of the aorta in relation to the pulmonary artery.

After creation of a model, that allows for simulation of the TGA pathology with the different spatial relationships of the great arteries, the different spiral anastomoses were performed. The Lecompte technique served as reference.

A tension and torsion free spiral connections of the great arteries was possible for the 0° to 35° relation of the aortic root to the pulmonary root without the use of prosthetic material. A further increasing rotation with angles of 45° needed some enlargement of the pulmonary root to construct a torsion and tension free anastomosis.

This study may renew the interest in the spiral physiological anatomic correction of simple TGA.

6. Zusammenfassung auf Deutsch

Einleitung

Die Transposition der großen Arterien (TGA) ist eine der häufigsten angeborenen zyanotischen Herzfehler. Bei dieser Erkrankung besteht eine fehlerhafte Verbindung der Hauptschlagader (Aorta) mit dem rechten und der Pulmonalarterie (Pulmonalis) mit dem linken Ventrikel des Herzens. Durch diese Fehlbildung sind der Lungen- und der Körperkreislauf voneinander getrennt und die Koronararterien, die der Aorta entspringen, werden mit nicht-oxygeniertem Blut aus dem rechten Ventrikel versorgt.

Die initialen Therapieversuche in den 50er Jahren bestanden aus einer Operation um die Gefäße wieder zu retransponieren und damit den Kreislauf in die normal, serielle Situation zu versetzen. Diese Versuche blieben jedoch aufgrund der Koronararterien-Retransposition erfolglos. 1975 gelang es erstmals Jatene bei einem Patienten mit TGA und einem Ventrikelseptumdefekt die operative Korrektur erfolgreich durchzuführen (Arterielle Switch Operation). Mit der Zeit wurden weitere Operationstechniken entwickelt, unter anderem die heute in der Regel durchgeführte Lecompte-Technik, bei der die Lungenarterie vor der Aorta platziert wird. Diese Technik machte zwar eine operative Korrektur ohne Fremdmaterialien möglich, stellt jedoch keine anatomisch korrekten Verhältnisse her. Diese Flussabnormalität kann langfristig zu Problemen wie z. B. Aortenwurzeldilatationen, Aortenklappeninsuffizienz oder Stenosen der Pulmonalarterienäste führen, wie in mehreren Studien belegt werden konnte.

2012 berichtete Sievers von einer erfolgreiche Serie von 5 Patienten, die 20 Jahre zuvor mit einer physiologisch korrekten, spiralförmigen ASO versorgt wurden. Bei einer Nachuntersuchung mittels 4D-Magnetresonanztomographie zeigten sich bei diesen Patienten nahezu anatomische und funktionelle Verhältnisse. Die Strömung war physiologischer als bei Patienten, die mit der Lecompte-Technik versorgt wurden. Diese Ergebnisse haben zu einem erneuten Interesse an der spiralförmigen TGA-

Korrektur geführt. Ziel der Arbeit war, die spiralförmigen Anastomosen der großen Gefäße in Abhängigkeit von der räumlichen Anordnung der großen Gefäße zueinander in-vitro zu evaluieren.

Methoden

Es wurde ein in-vitro Modell konstruiert, mit dessen Hilfe die spiralförmige Korrektur in Abhängigkeit von der variablen Lage der großen Gefäße zueinander untersucht werden konnte. Um die Verhältnisse einer TGA nachzubilden wurden Latex-Gefäße angefertigt und in einem Halte-Apparat fixiert. Anschließend wurden verschiedene chirurgische Techniken durchgeführt um die spiralförmige Korrektur in Abhängigkeit von der Lage der großen Gefäße zueinander zu simulieren. Als Referenz diente eine Korrektur nach Lecompte.

Ergebnisse

Das in-vitro Modell zeigt, dass es von einer anterior-posterior Lage der großen Gefäße (0° Position), bis zu einem Winkel der Aorta zur Pulmonalis von 35° nach rechts anterior möglich ist, ohne Fremdmaterial eine spiralförmige Arterielle Switch Operation durchzuführen. Eine intensive Mobilisierung der distalen großen Gefäße als auch eine optimierte Durchtrennung der großen Gefäße in Bezug auf die Durchtrennungshöhe sind zusätzlich hilfreich, diese Anastomosen spannungsfrei durchzuführen. Bei größeren Winkeln ist dies nur möglich indem an der Verbindung zwischen der Neo-Pulmonaliswurzel und der distalen Pulmonalarterie zusätzliches Material interponiert wird, obwohl die Dimensionen dieser Patchplastiken relativ gering sind, mit ca. 5 mm an der breitesten Stelle. Eine Korrektur nach Lecompte ist bei einem Winkel von 45° ohne Fremdmaterial möglich.

Diskussion

Der Einsatz von verschiedenen chirurgischen Techniken ermöglicht es, in einem in-vitro Modell, eine physiologische und anatomische korrekte spiralförmige Korrektur bis zu einem Winkel von 35° zwischen Aorta und Pulmonalarterie durchzuführen. Bei größeren Winkeln besteht die Notwendigkeit Fremdmaterial zu interponieren, welches im klinischen Umfeld z. B. aus frischem oder gestieltem Perikard bestehen könnte und somit über Wachstumspotential verfügt, zumal die Dimensionen dieser Erweiterungsflicken auch relativ gering gehalten werden können, mit maximal 5 mm an der breitesten Stelle. Durch diese in-vitro Versuche im Zusammenhang mit den ersten klinischen Ergebnissen nach spiralförmiger anatomischer Korrektur über 20 Jahre könnte ein neues Interesse an einer anatomisch und physiologisch korrekten spiralförmigen Korrektur der TGA aufkommen, um die potentiellen Nachteile der unphysiologischen Lecompte-Technik zu vermeiden.

7. References

1. Martins P, Castela E. Transposition of the great arteries. Orphanet J Rare Dis. 2008 Jan;3:27.
2. Kouchoukos N, Blackstone E, Hanley F, Kirklin J. Kirklin/Barratt-Boyes Cardiac Surgery. Elsevier Saunders Philadelphia; 2013.
3. Castaneda AR, Norwood WI, Jonas RA, Colon SD, Sanders SP, Lang P. Transposition of the great arteries and intact ventricular septum: anatomical repair in the neonate. Ann Thorac Surg. 1984 Nov;38(5):438–43.
4. Emmanouilides GC, Allen HD, Riemenschneider TA, Gutgesell HP. Moss and Adams' Heart Disease in Infants, Children, and Adolescents, Including the Fetus and Young Adult, 5th Ed. Williams & Wilkins Baltimore 1995.
5. Transposition of the Great Arteries [Internet]. Available from: http://pediatricheartspecialists.com/articles/detail/transposition_of_the_great_arteries
6. Wilcox B. Surgical Anatomy of the Heart. Gower Medical Publishing; 1992.
7. Gittenberger-de Groot AC, Poelmann RE, Bökenkamp R, Bogers AJJC. Development of coronary arteries in transposition of the great arteries. Transposition of the Great Arteries 25 years after Rashkind Balloon Septostomy. Steinkopff Verlag Darmstadt Springer-Verlag New York; 1992. p. 29–37.
8. Blalock A, Hanlon CR. Interatrial septal defect; its experimental production under direct vision without interruption of the circulation. Surg Gynecol Obstet. 1948 Aug;87(2):183–7.
9. Rashkind WJ. Creation of an Atrial Septal Defect Without Thoracotomy. JAMA. 1966 Jun 13;196(11):991.
10. Konstantinov IE, Alexi-Meskishvili V V, Williams WG, Freedom RM, Van Praagh R. Atrial switch operation: past, present, and future. Ann Thorac Surg. 2004 Jun;77(6):2250–8.
11. Senning A. Surgical correction of transposition of the great vessels. Surgery.

1959 Jun;45(6):966–80.

12. Mustard WT, Keith JD, Trusler GA, Fowler R, Kidd L. The Surgical Management of Transposition of the Great Vessels. J Thorac Cardiovasc Surg. 1964 Dec;48:953–8.

13. Mustard WT. Progress in the total correction of complete transposition of the great vessels. Vasc Dis. 1966 Jun;3(3):177–9.

14. Karl O-E. Evaluation und Langzeitverlauf des operativen Ergebnisses von Patienten mit einfacher Transposition der Grossen Arterien nach Senning Operation. Technische Universität München; 2007. Med. Diss. München 2007

15. Idriss FS, Goldstein IR, Grana L, French D, Potts WJ. A new technic for complete correction of transposition of the great vessels. An experimental study with a preliminary clinical report. Circulation. 1961 Jul;24:5–11.

16. Jatene AD, Fontes VF, Paulista PP, de Souza LC, Neger F, Galantier M, et al. Successful anatomic correction of transposition of the great vessels. A preliminary report. Arq Bras Cardiol. 1975 Aug;28(4):461–4.

17. Yacoub MH. The case for anatomic correction of transposition of the great arteries. J Thorac Cardiovasc Surg. 1979 Jul;78(1):3–6.

18. Yacoub MH, Radley-Smith R, Hilton CJ. Anatomical correction of complete transposition of the great arteries and ventricular septal defect in infancy. Br Med J. 1976 May 8;1(6018):1112–4.

19. Lecompte Y, Zannini L, Hazan E, Jarreau MM, Bex JP, Tu T V, et al. Anatomic correction of transposition of the great arteries. J Thorac Cardiovasc Surg. 1981 Oct;82(4):629–31.

20. Prêtre R, Tamisier D, Bonhoeffer P, Mauriat P, Pouard P, Sidi D, et al. Results of the arterial switch operation in neonates with transposed great arteries. Lancet. 2001 Jun 9;357(9271):1826–30.

21. Losay J, Touchot A, Serraf A, Litvinova A, Lambert V, Piot JD, et al. Late outcome after arterial switch operation for transposition of the great arteries. Circulation. 2001 Sep 18;104(12 Suppl 1):I121–6.

22. Culbert EL, Ashburn DA, Cullen-Dean G, Joseph JA, Williams WG,

Blackstone EH, et al. Quality of life of children after repair of transposition of the great arteries. Circulation. 2003 Aug 19;108(7):857–62.

23. Hourihan M, Colan SD, Wernovsky G, Maheswari U, Mayer JE, Sanders SP. Growth of the aortic anastomosis, annulus, and root after the arterial switch procedure performed in infancy. Circulation. 1993 Aug;88(2):615–20.
24. Losay J, Touchot A, Capderou A, Piot J-D, Belli E, Planché C, et al. Aortic valve regurgitation after arterial switch operation for transposition of the great arteries: incidence, risk factors, and outcome. J Am Coll Cardiol. 2006 May 16;47(10):2057–62.
25. Agnoletti G, Ou P, Celermajer DS, Boudjemline Y, Marini D, Bonnet D, et al. Acute angulation of the aortic arch predisposes a patient to ascending aortic dilatation and aortic regurgitation late after the arterial switch operation for transposition of the great arteries. J Thorac Cardiovasc Surg. 2008 Mar;135(3):568–72.
26. Fricke TA, D'Udekem Y, Richardson M, Thuys C, Dronavalli M, Ramsay JM, et al. Outcomes of the arterial switch operation for transposition of the great arteries: 25 years of experience. Ann Thorac Surg. 2012 Jul;94(1):139–45.
27. Wernovsky G, Mayer JE, Jonas RA, Hanley FL, Blackstone EH, Kirklin JW, et al. Factors influencing early and late outcome of the arterial switch operation for transposition of the great arteries. J Thorac Cardiovasc Surg. 1995 Feb;109(2):289–301; discussion 301–2.
28. Lange R, Cleuziou J, Hörer J, Holper K, Vogt M, Tassani-Prell P, et al. Risk factors for aortic insufficiency and aortic valve replacement after the arterial switch operation. Eur J Cardiothorac Surg. 2008 Oct;34(4):711–7.
29. Choi BS, Kwon BS, Kim GB, Bae EJ, Noh C Il, Choi JY, et al. Long-term outcomes after an arterial switch operation for simple complete transposition of the great arteries. Korean Circ J. 2010 Jan;40(1):23–30.
30. Sievers HH. The fate of the aortic root and PA bifurcation late after arterial switch OP. Transposition of Great Arteries, Old Story New Aspects 8th DHZB Lange Symposium. 2012.

31. Chiu I, Hung C. Restoration of Transposed Great Arteries With or Without Subpulmonary Obstruction to Nature [Internet]. Front Lines of Thoracic Surgery. InTech; 2012. Available from: http://www.intechopen.com/books/front-lines-of-thoracic-surgery/restoration-of-transposed-great-arteries-with-or-without-subpulmonary-obstruction-to-nature

32. Gutberlet M, Hoffmann J, Künzel E, Fleischer A, Sarikouch S, Beerbaum P, et al. Preoperative and postoperative imaging in patients with transposition of the great arteries. Radiologe. 2011 Jan;51(1):15–22.

33. Arnaiz E, Koolbergen D, Adsuar A, Hazekamp M. Surgery for supravalvular aortic stenosis - the three patch technique. Multimed Man Cardiothorac Surg. 2008;(Jan 1).

34. Hvass U, Khoury W, Subayi JB, Caliani J, Langlois J. [The autologous pericardial tube-flap. A new technic for restoring the continuity between the right ventricle and the pulmonary artery]. Presse Med. 1987 Dec 5;16(41):2069–71.

35. Zigras T. Biomechanics of Human Pericardium: A Comparative Study of Fresh and Fixed Tissue [Internet]. McGill University, Montreal, Canada; 2007. Available from: http://digitool.library.mcgill.ca/webclient/StreamGate?folder_id=0&dvs=1403806649703~252

36. Haluck RS, Richenbacher WE, Myers JL, Miller CA, Wise RK, Waldhausen JA. Pericardium as a thoracic aortic patch: glutaraldehyde-fixed and fresh autologous pericardium. J Surg Res. 1990 Jun;48(6):611–4.

37. Murakami T, Nakazawa M, Momma K, Imai Y. Impaired distensibility of neoaorta after arterial switch procedure. Ann Thorac Surg. 2000 Dec;70(6):1907–10.

38. Sievers HH, Lange PE, Arensman FW, Radley-Smith R, Yacoub MH, Harms D, et al. Influence of two-stage anatomic correction on size and distensibility of the anatomic pulmonary/functional aortic root in patients with simple transposition of the great arteries. Circulation. 1984 Aug;70(2):202–8.

39. Sakurai H, Matsuoka R, Furutani Y, Imamura S, Takao A, Momma K.

Expression of four myosin heavy chain genes in developing blood vessels and other smooth muscle organs in rabbits. Eur J Cell Biol. 1996 Feb;69(2):166–72.

40. Lalezari S, Hazekamp MG, Bartelings MM, Schoof PH, Gittenberger-De Groot AC. Pulmonary artery remodeling in transposition of the great arteries: relevance for neoaortic root dilatation. J Thorac Cardiovasc Surg. 2003 Oct;126(4):1053–60.

41. Jhang WK, Shin HJ, Park J-J, Yun T-J, Kim YH, Ko J-K, et al. The importance of neo-aortic root geometry in the arterial switch operation with the trap-door technique in the subsequent development of aortic valve regurgitation. Eur J Cardiothorac Surg. 2012 Nov;42(5):794–9; discussion 799.

8. Acknowledgements

I remain thankful to Prof. Dr. med. Sievers for entrusting me this very interesting subject, the possibility to perform research in congenital cardiac surgery, his support and drive to complete the thesis; to Dr. rer. hum. biol. Dipl. Ing. Michael Scharfschwerdt for his assistance and advice during the project; to Mr Michael Diwoky and Mr Tobias Frin for their assistance with the graphics and lay-out; to Mr Rolf Knobloch for his assistance in 'mass-production' of the models; to my girlfriend, family and friends for their continuous support, love and fun.

9. Curriculum Vitae

Personal data

Name	Léon Michel Putman
Date of birth	31.05.1985

Education

1997-2003	Pre-University Education, Erasmus College, Zoetermeer, Netherlands
2003-2010	Medical School, Erasmus University Medical Centre, Rotterdam, Netherlands
2005-2008	Master of Science in Clinical Research, Erasmus MC, Rotterdam, Netherlands

Employment History

2010-2011	Resident, Department of Cardio-Thoracic Surgery, Thoraxcentre, Erasmus University Medical Center, Rotterdam, Netherlands
2011-current	Resident in training, Department of Cardiac and Thoracic Vascular Surgery, University Clinic Schleswig-Holstein, Campus Lübeck, Germany

Publications

- **Putman LM**, van Gameren M, Meijboom FJ, de Jong PL, Roos-Hesselink JW, Witsenburg M, Takkenberg JJ, Bogers AJ. *Seventeen years of adult congenital heart surgery: a single centre experience*. Eur J Cardiothorac Surg. 2009 Jul;36(1):96-104

- van Gameren M, **Putman LM**, Takkenberg JJ, Bogers AJ. *Risk stratification for adult congenital heart surgery*. Eur J Cardiothorac Surg. 2011 Apr;39(4):490-4.

Presentations

-September 2009, 22nd Annual meeting European Association for Cardio-Thoracic Surgery, Lissabon, Portugal, "*Seventeen years of Adult Congenital Heart Surgery: a single centre experience*"

LM Putman, M van Gameren, FJ Meijboom, PL de Jong, JW Roos, M Witsenburg, JJM Takkenberg, AJJC Bogers.

-November 2010 COEUR Research seminar, Erasmus MC, Rotterdam, Netherlands, "*Primary surgery for aortic coarctation in adults*"

LM Putman, BP van Putte, AP Kappetein, M Witsenburg, AJJC Bogers.