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# *Hypoplastic left heart syndrome: surgical therapy*

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Dr. sc. Jelena Pabst von Ohain

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| Erster Gutachter: | Prof. Dr. Jürgen Hörer |
| Zweiter Gutachter: | Priv. Doz. Dr. Sebastian Michel |
| Dritter Gutachter: | Prof. Dr. Nikolaus Haas |

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|---|---|
| Dekan: | Prof. Dr. med. dent. Reinhard Hickel |

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# ABBREVIATIONS

| | |
|---|---|
| **BSCPA** | bidirectional superior cavopulmonary anastomosis |
| **CHD** | congenital heart disease |
| **HLHS** | hypoplastic left heart syndrome |
| **TCPC** | total cavopulmonary connection |

# ORIGINAL PUBLICATIONS TO THE TOPIC OF PROMOTION

## Paper I

Jelena Kasnar-Samprec*, Andreas Kühn*, Jürgen Hörer, Manfred Vogt, Julie Cleuziou, Rüdiger Lange, Christian Schreiber: Unloading of right ventricle by bidirectional superior cavopulmonary anastomosis in hypoplastic left heart syndrome patients promotes remodeling of systemic right ventricle but does not improve tricuspid regurgitation. The Journal of thoracic and cardiovascular surgery 09/2012; 144(5):1102-9. DOI:10.1016/j.jtcvs.2012.08.012

* Equally contributing authors

## Paper II

Julie Cleuziou, Jelena Kasnar-Samprec, Jürgen Hörer, Andreas Eicken, Rüdiger Lange, Christian Schreiber: Recoarctation After the Norwood I Procedure for Hypoplastic Left Heart Syndrome: Incidence, Risk Factors, and Treatment Options. The Annals of thoracic surgery 01/2013; 95(3):935-40. DOI:10.1016/j.athoracsur.2012.11.015

# AUTHOR CONTRIBUTION STATEMENT

## Contribution to Paper I

- Collection and assembly of data
- Data curation
- Formal analysis
- Validation
- Writing – original draft

The co-author Andreas Kühn, MD, who contributed equally to the publication, analysed all of the echocardiograms of the enrolled patients, and contributed significantly to data collection as well as reviewing and editing.

## Contribution to Paper II

- Collection and assembly of data
- Writing – review & editing

# INTRODUCTION

## Congenital heart disease

Congenital heart disease (CHD) accounts for 28% of all major congenital anomalies.[1] The worldwide incidence of CHD is estimated to 9 per 1,000 live births;[2] moderate and severe forms are present in about 6 per 1,000 live births.[3] Amongst all birth defects, CHD is the leading cause of illness and death in the infant age.[4] However, the advances in diagnostic methods, medical, interventional and surgical therapy of infants and children with CHD have resulted in one of the largest survival increments in medical history.[5-8] In developed countries, more than 90% of CHD patients are expected to survive the complete childhood.[9, 10] Survival to adulthood varies with the severity of CHD: 96-98% of patients with mild and moderate CHD and 56% of patients with severe CHD survive to adult ages.[11] The prevalence of patients with CHD in developed countries increased by >50% from 2000 to 2010.[12]

## Functionally single ventricle

Approximately 25% of the infants with CHD are born with a so-called „critical CHD“[4] and need of surgical or interventional treatment in the neonatal and infant age. Part of these patients has a functionally univentricular heart. This term includes all hearts in which one of the ventricles is anatomically or functionally inadequate, and the other, dominant ventricle has to support both the systemic and pulmonary circulation. Another common attribute of these hearts is that surgical therapy in the form of a biventricular correction is not achievable.[13]

The group of functionally univentricular hearts includes many different anatomical variations. Generally, it is possible to differentiate the dominant ventricle into the left, right or undifferentiated ventricle.[14] An anatomically single ventricle, without even a rudimentary part of the second ventricle, is very rare.[15, 16]

Many different anatomical variants of the functionally single ventricle are described, the most common being tricuspid atresia, double inlet left ventricle, pulmonary atresia with an intact interventricular septum, unbalanced common atrioventricular canal and the hypoplastic left heart syndrome.

Physiologically, the dominant ventricle supplies the systemic and pulmonary circulation in parallel. This parallel circulation poses a strain on the functionally single ventricle, and it leads to hypoxemia due to mixing of the oxygen-saturated and oxygen-desaturated blood. The function of the single ventricle and the competence of the atrioventricular valves play a significant role in the univentricular circulation.

The clinical picture of the newborns depends primarily on the amount of blood in the pulmonary circulation.[17] In this way, the functionally univentricular hearts can be divided into three groups, depending on the balance between the systemic and pulmonary circulation in the newborn age:

- balanced systemic and pulmonary circulation
    - few clinical symptoms[13, 18]
    - surgical treatment in the newborn age is not necessary
- restrictive pulmonary circulation
    - main symptom is cyanosis
    - a systemic-to-pulmonary shunt in the newborn age
- excessive pulmonary circulation
    - mainly symptoms of heart failure
    - without the obstruction of the systemic circulation → a pulmonary artery banding in the newborn age
    - with obstruction of the systemic circulation → a complex Norwood operation in the newborn age

The surgical therapy of all types of the functionally univentricular heart has a common objective: separating the pulmonary and systemic bloodstream while using the pump function of the dominant ventricle for the systemic circulation. The surgical strategy includes three steps:

- **Step I**: initial palliation in the newborn age for insuring unhindered systemic outflow as well as systemic and pulmonary venous return, and controlling the pulmonary blood flow[13]

- **Step II**: partial separation of the pulmonary and systemic bloodstreams by creating a superior cavopulmonary anastomosis, between 3-6 months of age
- **Step III**: complete separation of the pulmonary and systemic circulation by connecting the inferior vena cava to the pulmonary artery and completing the so-called Fontan-circulation, in the age of 18-48 months

## Hypoplastic left heart syndrome

First described by Noonan and Nadas in 1958,[19] hypoplastic left heart syndrome (HLHS) is the most common type of a functionally univentricular heart,[20] with an incidence of 2 to 3 per 10,000 births,[21, 22] accounting for 1 – 3% of all CHD.[23] HLHS is also one of the most complex and surgically challenging CHD.

HLHS consists of a variety of cardiac anomalies characterised by a hypoplastic left ventricle, atresia or stenosis of the aortic and mitral valve, and hypoplastic ascending aorta and aortic arch Figure 1.[24]

Newborns with HLHS are dependent on the persisting arterial duct, and the open atrial communication Figure 1.[23] The oxygenated blood from the pulmonary veins flows from the left atrium over the open atrial septum into the right atrium („left-to-right shunting“) and mixes there with the desaturated blood from the systemic veins. The “mixed” blood flows then through the dominant right ventricle in the main pulmonary artery. A part of the blood volume goes again in the pulmonary circulation. The other part of the blood flows over the persistent arterial duct in the aorta and facilitates the retrograde perfusion of the upper body part and the antegrade perfusion of the lower body part.[17]

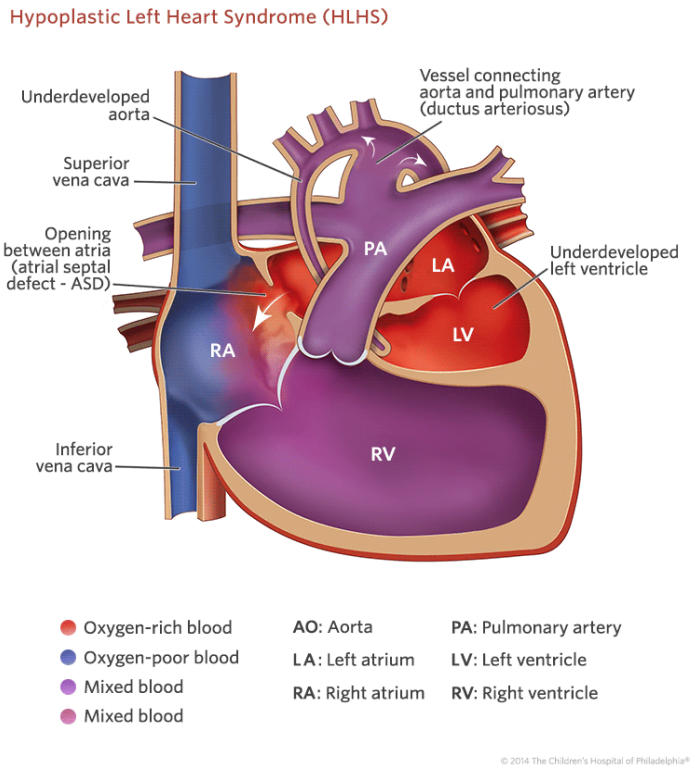


Figure 1. Hypoplastic left heart syndrome

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https://www.chop.edu/conditions-diseases/hypoplastic-left-heart-syndrome-hlhs

The systemic tricuspid valve is dysplastic approximately one-third of patients with HLHS, more commonly so in the presence of a non-atretic mitral valve.[25] Bileaflet tricuspid valve is present in up to 12% of patients; quadricuspid valve, clefts, and accessory orifices are less common.[25] The size of the tricuspid annulus is usually on the upper range of normal or above.

The theoretical work on surgical therapy of the HLHS started in the '60s and '70s[26, 27] with several unsuccessful surgical attempts.[28, 29] The first successful surgical treatment was performed by Norwood in the early '80s.[30-32]

## Norwood Operation

The Norwood operation is usually performed during the first ten days of life. To avoid possible complications, the surgery should not be delayed beyond the 2-3 weeks of life.[33, 34]

The goals of the Norwood operation Figure 2 are:

- unobstructed systemic circulation
    - using the pulmonary valve for the systemic outflow
    - augmenting the aorta
- unobstructed mixing of the blood from the pulmonary and the systemic veins
    - surgical widening of the atrial septal communication
- optimal pulmonary blood flow for enabling the growth of the pulmonary arteries
    - systemic-to-pulmonary shunt implantation

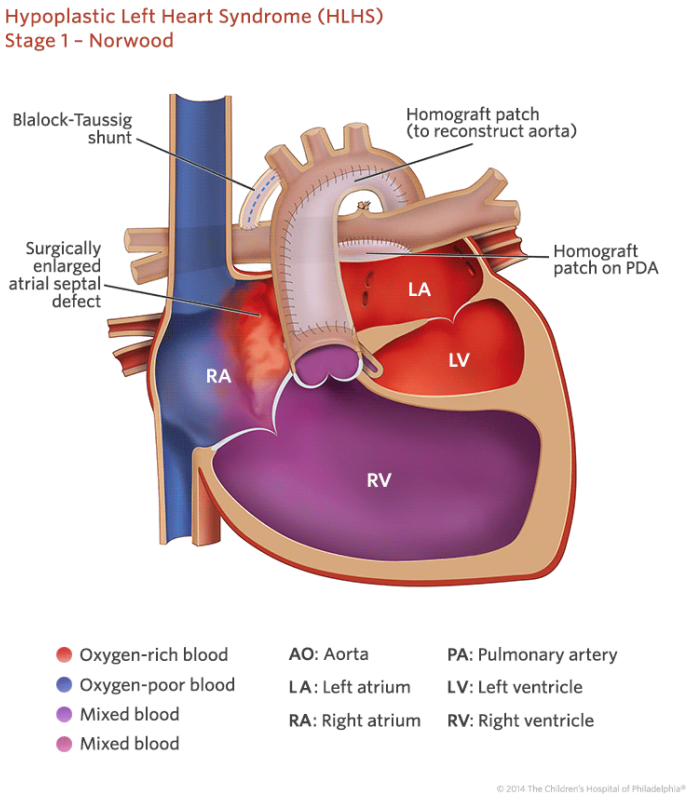


Figure 2. Norwood procedure


https://www.chop.edu/treatments/staged-reconstruction-heart-surgery

## Bidirectional superior cavopulmonary anastomosis

The bidirectional superior cavopulmonary anastomosis (BSCPA) is performed in the age of 3-6 months.[35] The timing for BSCPA differs significantly among centres, but it should not be performed while the pulmonary vascular resistance exceeds 2-3 Wood units.[36, 37]

During this operation, the superior vena cava is separated from the right atrium and sutured to the pulmonary artery Figure 3. The systemic-to-pulmonary shunt is divided. After BSCPA, unsaturated blood from the upper part of the body enters the pulmonary circulation without circulating through the heart.

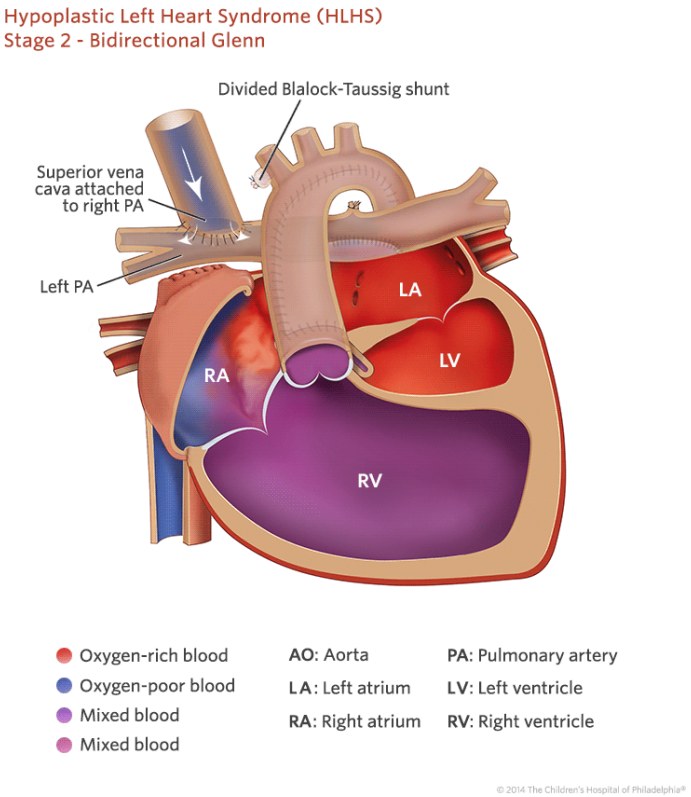


Figure 3. Bidirectional superior cavopulmonary anastomosis


https://www.chop.edu/treatments/staged-reconstruction-heart-surgery

The goals of the BSCPA are:

- partial separation of the pulmonary and systemic bloodstream
- providing sufficient "low pressure" pulmonary perfusion
- decline of the volume load of the right ventricle

## Total cavopulmonary connection

Total cavopulmonary connection (TCPC) is performed in the age of 18 to 36 months.[38] Some centres perform Fontan completion at an older age with comparable outcomes.[39]

The goal of the TCPC is the complete separation of the pulmonary and systemic circulation. This is achieved by disconnecting the vena cava inferior from the right atrium and suturing it to the pulmonary artery Figure 4. In this way, the desaturated blood from the lower body also flows to the pulmonary circulation without entering the heart.

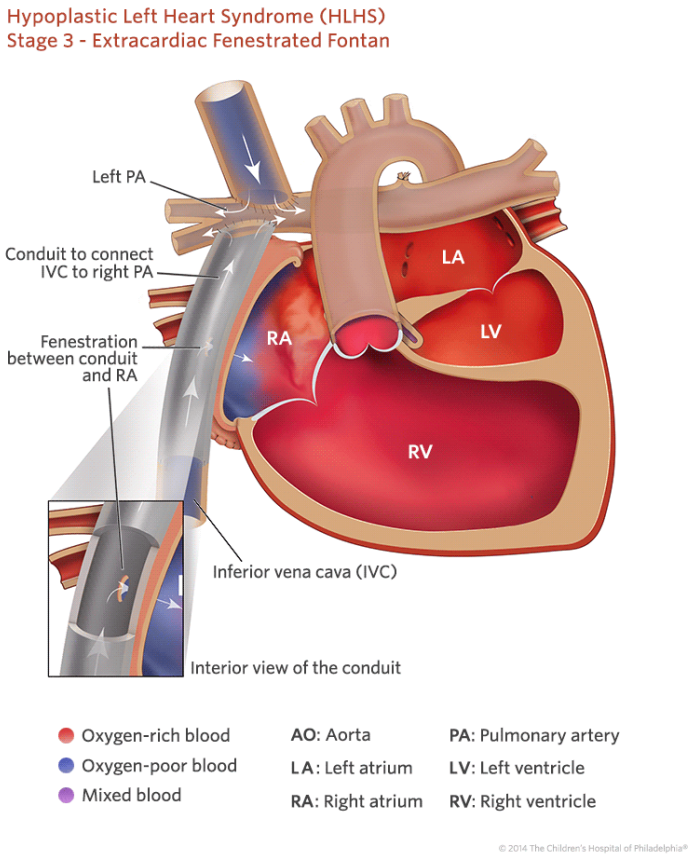


Figure 4. Total cavopulmonary connection


https://www.chop.edu/treatments/staged-reconstruction-heart-surgery

## Influence of bidirectional superior cavopulmonary anastomosis on the systemic right ventricle and the systemic tricuspid valve

High-grade of tricuspid valve insufficiency is a known risk factor for early and late morbidity and mortality[40, 41] in the patients with HLHS. The function of the tricuspid valve is influenced by the interaction of volume overload and consequent enlargement of the systemic right ventricle and the tricuspid annulus, morphological anomalies of the valve leaflets, and the pump-function of the systemic right ventricle.[42]

The construction of BSCPA changes the origin of the pulmonary bloodstream and decreases the volume of blood entering the systemic right ventricle.[43] The reduction of the ventricular volume slows down the dilation of the tricuspid valve annulus.[44] It has been reported that the grade of insufficiency of the atrioventricular valve in patients with a functionally univentricular heart can decrease after BSCPA, without simultaneous valve surgery.[45]

We aimed to evaluate the effect of BSCPA and consequent reduction of volume load on the systemic right ventricle and the systemic tricuspid valve in patients with HLHS.

## Re-coarctation after the Norwood operation

Early mortality following the Norwood operation in patients with HLHS has declined in the past years to approximately 10-22%.[46] Serious complications which might occur after the Norwood operation are excessive or inadequate pulmonary blood flow, impairment of coronary artery perfusion, and neoaortic arch obstruction.[47] The reported rate of re-coarctation of the aorta is 10-36%.[48, 49] Re-coarctation is associated with decreased ventricular function and tricuspid regurgitation, and consequent morbidity and mortality.[50] Recurrent or residual aortic arch obstruction may be technique and materials dependent.[51-53]

Our study aimed to determine the incidence, evaluate the risk factors, and analyse therapy options of re-coarctation after Norwood operation in patients with HLHS.

# ZUSAMMENFASSUNG

## Unloading of right ventricle by bidirectional superior cavopulmonary anastomosis in hypoplastic left heart syndrome patients promotes remodeling of systemic right ventricle but does not improve tricuspid regurgitation

*Jelena Kasnar-Samprec*, Andreas Kühn*, Jürgen Hörer, Manfred Vogt, Julie Cleuziou, Rüdiger Lange, Christian Schreiber*

J Thorac Cardiovasc Surg. 2012 Nov;144(5):1102-8.

* Equally contributing authors

**Ziel**: Das Ziel unserer Studie war die Beurteilung des Effekts der bidirektionalen superioren cavopulmonalen Verbindung (BSCPA) zur Verringerung der Volumenbelastung des systemischen rechten Ventrikels und der systemischen Trikuspidalklappe bei Patienten mit hypoplastischem Linksherz Syndrom (HLHS).

**Patienten und Methoden**: Neunzig aufeinanderfolgende Patienten mit HLHS, die die frühpostoperative Periode nach BSCPA überlebt hatten, wurden analysiert. Zwei Echokardiogramme wurden durch einen erfahrenen Spezialisten bewertet: eines vor der BSCPA und das zweite beim letzten Follow-Up vor der totalen cavopulmonalen Anastomose. Die folgenden Parameter wurden beurteilt: Grad der Trikuspidalklappeninsuffizienz, die Morphologie der Trikuspidalklappe bei Klappeninsuffizienz, der Durchmesser des Trikuspidalklappenannulus, tricuspid annular plane systolic excursion (TAPSE) und die rechtsventrikuläre Pumpfunktion.

**Ergebnisse**: In den Echokardiogrammen, die im Median fünf Tage vor der BSCPA durchgeführt wurden, gab es keine Trikuspidalklappeninsuffizienz bei 11 Patienten, minimale bei 37 Patienten, geringgradige bei 24 Patienten und mittelgradige bei 11 Patienten. In den Echokardiogrammen, die im Medianalter von 17 Monate durchgeführt wurden, gab es keine Trikuspidalklappeninsuffizienz bei 14 Patienten, minimale bei 37 Patienten, geringgradige bei 21 Patienten, mittelgradige bei 6 Patienten und hochgradige bei 5 Patienten. Der Unterschied zwischen der Trikuspidalklappeninsuffizienz vor und nach der BSCPA war statistisch nicht signifikant. Die meisten Patienten mit einer mittelgradigen und hochgradigen

Trikuspidalklappeninsuffizienz hatten eine morphologisch auffällige Trikuspidalklappe, mit einem Prolaps des anterioren Segels und/oder einer Restriktion des posterioren Segels.

Der Durchmesser des Trikuspidalklappenannulus ist nach der BSCPA in Patienten mit mittelgradigen und hochgradigen Trikuspidalklappeninsuffizienz gleichgeblieben; bei den verbliebenen Patienten ist er kleiner geworden.

Vor der BSCPA war das Verhältnis von TAPSE zu Alter bei allen Patienten ähnlich. Nach der BSCPA war das Verhältnis von TAPSE zu Alter bei Patienten mit mittelgradiger oder hochgradiger Trikuspidalklappeninsuffizienz größer als beim Rest der Patienten.

Die Funktion des systemischen rechten Ventrikels war normal in 95% der Patienten vor der BSCPA und 87% der Patienten nach der BSCPA. Die postoperative Pumpfunktion des rechten Ventrikels war nicht abhängig vom Durchmesser des Trikuspidalklappenannulus.

**Kommentar:** In unserer Studie hat sich nach BSCPA der Grad der Trikuspidalklappeninsuffizienz nicht geändert. Die relative Größe des Trikuspidalklappenannulus hat sich verkleinert, bedingt wahrscheinlich durch die verringerte Volumenbelastung nach der BSCPA. Bei Patienten mit mittelgradiger und hochgradiger Trikuspidalklappeninsuffizienz hat sich der Annulus nicht verändert und war größer als beim Rest der Patienten. Die Segel der systemischen Trikuspidalklappe waren nur selten normal bei Patienten mit mittelgradiger und hochgradiger Klappeninsuffizienz.

Nach der BSCPA war TAPSE nur bei Patienten mit weniger als moderater Trikuspidalklappeninsuffizienz signifikant kleiner. TAPSE ist direkt proportional zur Vorlast des rechten Ventrikels: diese ist vor der BSCPA höher als danach. TAPSE ist in Präsenz einer mittelgradigen oder hochgradigen Trikuspidalklappeninsuffizienz größer, weil der Unterschied zwischen systolischem und diastolischem rechtsventrikulären Volumen größer ist.

In unserer Studie war die Prävalenz einer eingeschränkten rechtsventrikulären Pumpfunktion nach der BSCPA größer als präoperativ. Eine mögliche Erklärung dafür ist, dass der morphologisch rechte Ventrikel beim HLHS den systemischen Kreislauf unterstützen muss. Um eine Erklärung für dieses Phänomen zu finden, müssten weitere Studien die genaue Morphologie und Funktion des systemischen rechten Ventrikels und dessen Interaktion mit dem vorhandenen hypoplastischen linken Ventrikel klären.

**Schlussfolgerung**: Unsere Ergebnisse haben gezeigt, dass weniger Volumenbelastung durch BSCPA den Durchmesser der systemischen Trikuspidalklappe verringern kann, ohne dass es zwingend zu einer Verringerung der Insuffizienz der Trikuspidalklappe führt. Man kann vermuten, dass sich der Grad der Trikuspidalklappeninsuffizienz nach der BSCPA ohne chirurgische Behandlung nicht ändern wird. Eine Trikuspidalklappenrekonstruktion sollte deswegen während der BSCPA in Betracht gezogen werden.

## Recoarctation after the Norwood I procedure for hypoplastic left heart syndrome: incidence, risk factors, and treatment options

*Julie Cleuziou, Jelena Kasnar-Samprec, Jürgen Hörer, Andreas Eicken, Rüdiger Lange, Christian Schreiber.*

Ann Thorac Surg. 2013 Mar;95(3):935-40.

**Ziel**: Das Ziel unserer Studie war die Feststellung der Inzidenz, die Evaluierung der Risikofaktoren, sowie die Analyse der Therapieoptionen für die Recoarctation nach einer Norwood Operation bei Patienten mit hypoplastischem Linksherz Syndrom (HLHS).

**Patienten und Methoden**: In dieser Studie wurden 124 HLHS Patienten mit durchgeführter Norwood Operation analysiert. Die folgenden Faktoren waren in der Risikoanalyse eingeschlossen: Alter, Gewicht, Geschlecht, Durchmesser der nativen Aorta, chirurgische Technik und Patchmaterial für die Rekonstruktion der Aorta. In der Angiographie vor der bidirektionalen superioren cavopulmonalen Anastomose (BSCPA) wurde der Druckgradient zwischen der Aorta ascendens und der Aorta descendens, sowie die Notwendigkeit einer Dilatation der Recoarctation festgestellt.

**Ergebnisse**: Eine Recoarctation ist bei 13% der Patienten, durchschnittlich 6.4±5 Monate nach der Norwood Operation diagnostiziert worden. Die geschätzte Freiheit von der Recoarctation nach der Norwood Operation lag bei 89.5% nach 6 Monate, 88.2% nach 12 Monate und 84.9% nach 10 Jahren.

In der univariaten Analyse hat keiner der analysierten morphologischen oder chirurgischen Faktoren das Einstehen einer Recoarctation beeinflusst.

Der durchschnittliche Druckgradient bei Patienten mit einer Recoarctation lag bei 24±16 mmHg und damit signifikant höher als bei den Patienten ohne Recoarctation. Ein Patient verstarb vor der Therapie der Recoarctation. Bei den restlichen 12 Patienten mit Recoarctation wurde eine Ballondilatation bei 10 Patienten und eine Operation bei 2 Patienten durchgeführt. Nach der interventionellen oder chirurgischen Therapie hat sich der Druckgradient signifikant auf 6.3±4 mmHg verringert.

**Kommentar:** In unserer Studie war die Inzidenz einer Recoarctation nach einer Norwood Operation bei Pateinten mit HLHS mit 13% niedrig.

Obwohl das Patchmaterial einer der vermuteten Risikofaktoren für eine Recoarctation ist, konnte das unsere Studie nicht bestätigen. Keiner der analysierten morphologischen oder chirurgischen Faktoren hat das Einstehen einer Recoarctation signifikant beeinflusst.

Die Therapieoptionen für eine Recoarctation sind interventionelle (Ballondilatation, Stent-Implantation) und chirurgische Prozeduren. Nach Ballondilatationen sind keine Komplikationen entstanden. Bei einigen Patienten musste aber eine Re-Dilatation vor der totalen cavopulmonalen Anastomose durchgeführt werden. Es traten keine Komplikationen nach chirurgischer Revision der Recoarctation auf.

**Schlussfolgerung**: Eine niedrige Rate der Recoarctation nach der Norwood Operation bei HLHS Patienten ist durch Standardisierung der chirurgischen Technik mit einer kompletten Resektion des Ductus-Gewebe und einer zusätzlichen Erweiterung der distalen Anastomose erreichbar. Eine Recoarctation kann bei der Feststellung der Diagnose durch Ballonangioplastie erfolgreich behandelt werden. Eine chirurgische Therapie der Recoarctation ist selten erforderlich.

# ABSTRACT

## Unloading of right ventricle by bidirectional superior cavopulmonary anastomosis in hypoplastic left heart syndrome patients promotes remodeling of systemic right ventricle but does not improve tricuspid regurgitation

*Jelena Kasnar-Samprec*, Andreas Kühn*, Jürgen Hörer, Manfred Vogt, Julie Cleuziou, Rüdiger Lange, Christian Schreiber*

J Thorac Cardiovasc Surg. 2012 Nov;144(5):1102-8.

* Equally contributing authors

**Objective**: Our study aimed to evaluate the effect of bidirectional superior cavopulmonary anastomosis (BSCPA) and consequent reduction in volume load on the systemic right ventricle and the systemic tricuspid valve in patients with hypoplastic left heart syndrome (HLHS).

**Patients and methods**: Ninety consecutive patients with HLHS, who were early-survivors after BSCPA were included in the study. Two ultrasound examinations from each patient were re-evaluated by an experienced paediatric cardiologist: one prior to BSCPA and the second prior to completing the Fontan circulation. The degree of tricuspid regurgitation, the morphology of the systemic tricuspid valve, the diameter of the tricuspid annulus, tricuspid annular plane systolic excursion (TAPSE), and the right ventricular function were noted.

**Results**: In the echocardiograms performed in median five days before BSCPA, tricuspid regurgitation was absent in 11 patients, trivial in 37 patients, mild in 24 patients, and moderate in 11 patients. In the echocardiograms performed in age of median 17 months, tricuspid regurgitation was absent in 14 patients, trivial in 37 patients, mild in 21 patients, moderate in 6 patients, and severe in 5 patients. The change in grade of tricuspid regurgitation before and after BSCPA was not statistically significant. Most of the patients with a moderate and severe tricuspid regurgitation had a structurally abnormal tricuspid valve, most commonly a prolapse of the anterior leaflet and/or a restriction of the posterior leaflet.

The diameter of the tricuspid valve annulus stayed the same after BSCPA in patients with moderate and severe tricuspid regurgitation; in the remaining patients, it decreased.

Prior to BSCPA, the TAPSE/age ratio was similar in all patients. After BSCPA, the TAPSE/age ratio was larger in patients with postoperative moderate or severe tricuspid regurgitation, than in the remaining patients.

The function of the systemic right ventricle was normal in 95% of the patients before BSCPA and 87% of the patients after BSCPA. The postoperative function of the right ventricle was not dependent on the diameter of the tricuspid annulus.

**Comment:** In our study, the grade of the tricuspid valve regurgitation did not change after the BSCPA. The diameter of the tricuspid annulus decreased, most likely due to a reduction of the volume load. In patients with moderate or severe tricuspid regurgitation, the annulus did not change and was larger than in the remaining patients. The leaflets of the systemic tricuspid valve were only rarely described as normal in patients with moderate or severe regurgitation.

TAPSE was significantly reduced after BSCPA only in patients without moderate or severe tricuspid regurgitation.

In our cohort, more patients had a reduced function of the systemic RV after BSCPA than before the operation. A partial explanation is that a morphologically right ventricle must sustain the systemic blood flow in patients with HLHS. Additional investigation of the morphology and function of the systemic right ventricle and its interaction with the hypoplastic left ventricle are necessary to explain this result.

**Conclusion**: Our study suggests that the reduction in volume load reduces the size of the systemic tricuspid annulus, without necessarily influencing the valve regurgitation. It can be assumed that the degree of tricuspid regurgitation won't change after the BSCPA without valve surgery. Therefore, tricuspid valve repair should be carefully discussed prior to performing BSCPA.

## Recoarctation after the Norwood I procedure for hypoplastic left heart syndrome: incidence, risk factors, and treatment options

*Julie Cleuziou, Jelena Kasnar-Samprec, Jürgen Hörer, Andreas Eicken, Rüdiger Lange, Christian Schreiber.*

Ann Thorac Surg. 2013 Mar;95(3):935-40.

**Objective**: Our study aimed to determine the incidence, evaluate risk factors, and analyse therapy options of re-coarctation after Norwood operation in patients with hypoplastic left heart syndrome (HLHS).

**Patients and methods**: One hundred twenty-four consecutive patients with HLHS who underwent the Norwood operation were included in the study. The following factors were included in the risk analysis: age, weight, gender, the diameter of the native ascending aorta, the surgical technique and the patch material. The difference in the pressure in the ascending and the descending aorta, as well as the need for dilatation of a re-coarctation, was noted on the angiography before bidirectional superior cavopulmonary anastomosis (BSCPA).

**Results**: Re-coarctation was diagnosed in 13% of the patients at a mean time of 6.4±5 months following the Norwood operation. Freedom from re-coarctation was 89.5% at six months, 88.2% at 12 months and 84.9% at ten years.

In the univariate analysis, none of the examined morphologic or surgical factors influenced the development of a re-coarctation.

The mean pressure difference in patients with a re-coarctation was 24±16 mmHg, and significantly higher than in patients without a re-coarctation. One patient demised before the re-coarctation could be treated. In the remaining 12 patients, balloon angioplasty was performed in 10 patients while two required surgical relief of the obstruction. After the interventional or surgical procedure, the difference in pressures significantly decreased to 6.3±4 mmHg.

**Comment:** In our cohort, the incidence of re-coarctation after the Norwood operation in HLHS patients was low, with 13%.

Although the patch material is one of the implicated risk factors for developing a re-coarctation after a Norwood operation in the HLHS patients, our study could not confirm this. All of the examined patient characteristics and surgical factors did not significantly influence the recurrence of an aortic arch obstruction.

Treatment options for re-coarctation include interventional (balloon angioplasty, stent implantation) and surgical procedures. No complications occurred after balloon angioplasty. However, several patients had to undergo a re-dilatation prior to total cavopulmonary connection. No complications occurred after the surgical relief of the re-coarctation

**Conclusion**: A low frequency of re-coarctation following the Norwood procedure in HLHS patients can be accomplished using a standardised surgical technique which includes complete resection of the arterial duct and a careful broadening of the anastomosis at the distal end of the descending aorta. A re-coarctation can be treated successfully by balloon angioplasty at the time of the diagnosis. Surgical treatment of the re-coarctation is rarely required.

# PAPER I

# Unloading of right ventricle by bidirectional superior cavopulmonary anastomosis in hypoplastic left heart syndrome patients promotes remodeling of systemic right ventricle but does not improve tricuspid regurgitation

Jelena Kasnar-Samprec, MD, PhD,[a] Andreas Kühn, MD,[b] Jürgen Hörer, MD, PhD,[a] Manfred Vogt, MD, PhD,[b] Julie Cleuziou, MD,[a] Rüdiger Lange, MD, PhD,[a] and Christian Schreiber, MD, PhD[a]

**Objective:** To evaluate the influence of volume unloading by bidirectional superior cavopulmonary anastomosis on the systemic right ventricle in patients with hypoplastic left heart syndrome.

**Methods:** A total of 90 consecutive patients with hypoplastic left heart syndrome, who had survived the early postoperative period after bidirectional superior cavopulmonary anastomosis, were studied. Seven patients were excluded because of tricuspid valve surgery before or in association with bidirectional superior cavopulmonary anastomosis. The echocardiograms of the remaining 83 patients were reevaluated for tricuspid valve regurgitation and the size of the tricuspid annulus before bidirectional superior cavopulmonary anastomosis and at the last available follow-up examination before total cavopulmonary connection.

**Results:** Echocardiograms were performed a median of 5 days before bidirectional superior cavopulmonary anastomosis. Tricuspid valve regurgitation was graded as 0 in 11 patients, I in 37 patients, II in 24 patients, and III in 11 patients. Follow-up echocardiograms were performed a median of 17 months after bidirectional superior cavopulmonary anastomosis. Postoperatively, tricuspid valve regurgitation was graded as 0 in 14 patients, I in 37 patients, II in 21 patients, III in 6 patients, and IV in 5 patients. Postoperatively, the mean *Z* value of the tricuspid annulus stayed the same in patients with significant tricuspid valve regurgitation (grade III or IV) after bidirectional superior cavopulmonary anastomosis but had decreased in the remaining patients. No significant change was seen in the level of tricuspid valve regurgitation after bidirectional superior cavopulmonary anastomosis compared with the preoperative data.

**Conclusions:** The relative size of the tricuspid annulus in patients with hypoplastic left heart syndrome decreases after bidirectional superior cavopulmonary anastomosis, most likely owing to volume unloading and promotion of the remodeling of the systemic right ventricle. However, this remodeling of the right ventricle does not improve the grade of tricuspid regurgitation. (J Thorac Cardiovasc Surg 2012;144:1102-9)

Significant tricuspid valve (TV) regurgitation (TR) is a risk factor for early and late adverse outcomes[1,2] in the treatment of patients with hypoplastic left heart syndrome (HLHS). TV function in these patients is determined by several interrelated factors, including volume overload and dilation of the right ventricle (RV), dilation of the TV annulus, structural abnormalities of the tricuspid leaflets, and deteriorating RV function.[3]

Three-stage surgical univentricular palliation is an established treatment strategy for HLHS.[4] The construction of a bidirectional superior cavopulmonary anastomosis (BSCPA), which follows the initial Norwood operation, alters the source of pulmonary blood flow and reduces the volume load of the systemic RV.[5] The decreased ventricular volume seems to reduce the rate of tricuspid annulus dilation.[6] Some studies have suggested that the regurgitation of the atrioventricular valve in single-ventricle patients might improve after BSCPA without concomitant valvuloplasty.[7]

The objective of our study was to elucidate the influence of volume unloading by BSCPA on the systemic RV in the patients with HLHS and its influence on systemic TR. According to the results obtained, we wanted to discuss the possible clinical implications regarding TV repair at BSCPA.

## PATIENTS AND METHODS

### Patient Selection

We identified all patients with HLHS who had undergone Norwood I palliation and BSCPA from 2001 to 2010 from our institutional cardiothoracic surgical database. We performed a retrospective review of 90

From the Departments of Cardiovascular Surgery[a] and Pediatric Cardiology and Congenital Heart Defects,[b] Deutsches Herzzentrum München an der Technischen Universität München, Munich, Germany.

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Address for reprints: Jelena Kasnar-Samprec, MD, PhD, Department of Cardiovascular Surgery, Deutsches Herzzentrum München an der Technischen Universität München, Lazarettstraße 36, Munich 80636 Germany (E-mail: samprec@dhm.mhn.de).

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**Abbreviations and Acronyms**

HLHS = hypoplastic left heart syndrome
RV = right ventricle/right ventricular
TAPSE = tricuspid annular plane systolic excursion
TR = tricuspid valve regurgitation
TV = tricuspid valve

consecutive patients who had survived the early postoperative period after BSCPA. A total of 7 patients, in whom TV reconstruction or replacement had to be performed before (n = 2) or at BSCPA (n = 5) because of severe TR, were excluded from the final study group.

### Echocardiographic Examination

Two echocardiograms from each patient (n = 83) were reevaluated by a single experienced observer: 1 before BSCPA (preoperatively) and the other at the last available follow-up point before total cavopulmonary connection (postoperatively).

The following measures were obtained: the degree of TR, morphology of the TV in the presence of significant regurgitation, the size of the TV annulus, tricuspid annular plane systolic excursion (TAPSE), and RV function. TR was graded qualitatively into 1 of 5 levels: absent (0), trivial (I), mild (II), moderate (III), or severe (IV). The grade was determined by the width and length of the insufficiency jet. Significant TR was defined as grade III or IV. The pathologic features of the TV were described for all patients with significant TR. TV annulus was measured as the maximum distance between the TV leaflet hinge points in the apical 4-chamber view. The size of the TV annulus was standardized to the body surface area of the patient at the time of echocardiography.[8] TAPSE was measured using 2-dimensional echocardiography-guided M-mode recordings from the apical 4-chamber view, with the cursor placed at the free wall of the tricuspid annulus. To be able to compare the pre- and postoperative TAPSE values of the children with HLHS, the mean expected TAPSE values for age in the normal population were determined for each patient preoperatively and postoperatively ("normal TAPSE for age").[9] The measured TAPSE values were then compared with these values to obtain a TAPSE/age ratio according to the formula: TAPSE/age ratio = (measured TAPSE/normal TAPSE for age) × 100. A ratio of 100% would mean that the measured value is the same as the value for a healthy child of the same age. RV function was qualitatively graded as normal, mildly, moderately, or severely depressed ("eye balling").

### Missing Values

The necessary loops for obtaining all the parameters could not be obtained from some of the echocardiograms performed during the early part of the study period. Consequently, 18 preoperative and 6 postoperative values were missing for TV annulus and 20 preoperative and 6 postoperative values for TAPSE were missing. The number of patients with missing values was not significantly different between the examined groups for any of these parameters.

### Statistical Analysis

Descriptive statistics are described as frequencies and percentages for categorical variables. Continuous variables are expressed as the mean ± standard deviation, if normally distributed, or median and range for a non-normal distribution. Fischer's exact test or McNemar's test was performed to detect significant differences between groups (2-tailed tests were used for all analyses). Continuous variables were compared between groups using the 2-tailed unpaired Student *t* test and within the groups using the 2-tailed paired Student's *t*-test. All data were analyzed using SPSS software, version 19.0 (SPSS, Inc, Chicago, Ill).

The institutional review board approved the present retrospective follow-up study. The requirement for informed consent was waived. We all had full access to the data and take full responsibility for the integrity of the data.

## RESULTS

The mean age at BSCPA was 4.4 ± 1.5 months, and mean weight was 5.29 ± 0.89 kg. Echocardiograms before BSCPA were performed a median of 5 days (range, 0-25) preoperatively. Follow-up echocardiograms were performed a median of 17 months (range, 7 days to 57 months) after BSCPA. For 5 patients, the follow-up echocardiogram was performed 7 to 14 days postoperatively and for another 4 patients 15 to 21 days postoperatively. All these children had travelled for surgery from another country, and details of more recent echocardiograms could not be obtained for the present study. In the remaining 74 patients, a follow-up echocardiogram was performed at least 1 month postoperatively. The mean age at the completion of univentricular palliation was 20.7 ± 8.0 months.

### TV Regurgitation

Before BSCPA, TR was graded as 0 in 11 patients, I in 37 patients, II in 24 patients, and III in 11 patients (Figure 1, *A*). Postoperatively, TR was graded as 0 in 14 patients, I in 37 patients, II in 21 patients, III in 6 patients, and IV in 5 patients (Figure 1, *B*). No significant change was seen in the level of TR after BSCPA compared with the preoperative data ($P = .68$, patients with TR grade $\geq$ II and $P = 1.00$, patients with TR grade $\geq$ III).

The comparison of pre- and postoperative TR on an individual patient basis is presented in Table 1. The echocardiographic details of each patient with significant TR, including the underlying pathologic features of the tricuspid leaflets, are listed in Table 2.

The patients were divided into 3 groups. Group 1 included 65 patients who did not have significant TR either before or after BSCPA. Group 2 included 7 patients who had significant TR preoperatively but after BSCPA had nonsignificant TR. Finally, group 3 included 11 patients with significant TR postoperatively, regardless of the preoperative finding; before BSCPA, 4 had significant and 7 nonsignificant TR. The median follow-up period was similar in all groups (group 1, 17.0 months; group 2, 15.8 months; and group 3, 18.5 months).

### TV Annulus

Figure 2 shows the mean *Z* value of the TV annulus before and after BSCPA for all 3 groups. The mean *Z* value of the TV annulus before BSCPA was significantly lower in group 1 (0.98 ± 0.82) than in group 2 (1.84 ± 0.69; $P = .015$) and tended to be lower than in group 3 (1.54 ± 0.66; $P = .071$).

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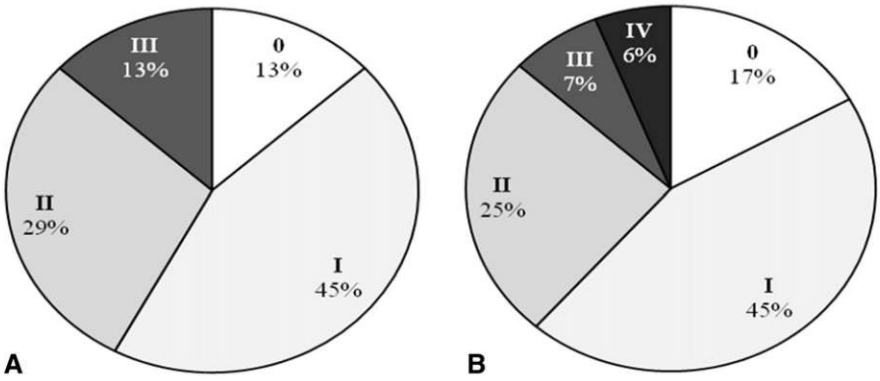


**FIGURE 1.** Percentage of patients according to grade of tricuspid regurgitation, (A) before and, (B) after bidirectional superior cavopulmonary anastomosis.

No statistically significant difference was seen in the preoperative *Z* value of the tricuspid annulus between groups 2 and 3 ($P = .421$). After BSCPA, the *Z* value of the tricuspid annulus was lower in group 1 ($0.41 \pm 0.70$) than in group 3 ($1.32 \pm 0.85$; $P = .008$), while no statistically significant difference was found between group 2 ($0.87 \pm 0.54$) and group 1 ($P = .101$) or group 3 ($P = .215$).

### Tricuspid Annular Plane Systolic Excursion

Figure 3 shows the TAPSE/age ratio before and after BSCPA for all 3 groups. Before BSCPA, the TAPSE/age ratio was the same in all patients, lower than the expected value for the same age group of healthy patients. After BSCPA, the TAPSE/age ratio was greater in group 3 ($62.38 \pm 9.58$) than in group 1 ($51.64 \pm 8.97$; $P = .006$) or group 2 ($50.41 \pm 10.52$; $P = .033$), while no difference was noted between groups 1 and 2 ($P = .775$).

### RV Function

Before BSCPA, RV function was normal in 79 patients (95%), mildly reduced in 3 (4%; 1 patient in group 1 and 2 patients in group 3), and moderately reduced in 1 patient (in group 2; 1%). Reduced RV function was found more often in patients with significant TR than in those with nonsignificant TR. After BSCPA, RV function was normal in 72 patients, mildly reduced in 8 (5 in group 1, 1 in group 2, and 2 in group 3), moderately reduced in 1 patient (in group 3), and severely reduced in 2 patients (both in group 1).

In 3 of 4 patients with preoperative RV dysfunction, the function normalized after BSCPA. In 1 patient (with mildly decreased RV function), the finding was the same before and after BSCPA. In the remaining 10 patients with reduced RV function postoperatively, RV dysfunction was seen for the first time after BSCPA.

### Relationship Among Relative Size of Tricuspid Annulus, TAPSE, and RV Function

Patients with a preoperative *Z* value of the tricuspid annulus greater than 1.5 also had a larger TAPSE/age ratio ($68.3 \pm 12.1$) than the patients with a smaller annulus ($58.4 \pm 6.6$; $P < .001$). Postoperatively, this relationship between the TAPSE values and the *Z* value of the tricuspid annulus could not be confirmed ($P = .115$).

Postoperative RV function was not dependent on the preoperative ($P = .862$) or postoperative ($P = .179$) *Z* value of the tricuspid annulus.

The patients with postoperatively reduced RV function had a lower postoperative TAPSE/age ratio ($44.1\% \pm 10.8\%$) than the patients with normal RV function ($54.4\% \pm 9.0\%$; $P = .015$).

**TABLE 1. Comparison of pre- and postoperative tricuspid regurgitation**

| | Postoperative TR | | | | |
|---|---|---|---|---|---|
| **Preoperative TR** | **0** | **I** | **II** | **III** | **IV** |
| 0 | 6* | 3† | 2† | 0† | 0† |
| I | 5‡ | 24* | 7† | 1† | 0† |
| II | 2‡ | 9‡ | 7* | 3† | 3† |
| III | 1‡ | 1‡ | 5‡ | 2* | 2† |
| IV | 0‡ | 0‡ | 0‡ | 0‡ | 0* |

*TR,* Tricuspid regurgitation; *BSCPA,* bidirectional superior cavopulmonary anastomosis. *Patients in whom TR severity stayed the same after BSCPA. †Patients in whom TR severity increased after BSCPA. ‡Patients in whom TR severity decreased after BSCPA.

## DISCUSSION

Significant TR is known to reduce the long-term hemodynamic performance of the systemic RV in patients with HLHS and is a risk factor for early and late adverse events.[1,2] Some studies have suggested that the grade of TR will decrease after BSCPA without surgical intervention on the TV.[7] Our data have shown that effective volume unloading might reduce TV size but does not necessarily influence TR.

### TV Regurgitation

The prevalence of significant TR in our patients was 13% before BSCPA, similar to previously reported data.[10] The

**TABLE 2. Echocardiographic details of patients with significant tricuspid regurgitation**

| Group | Patient ID | Interval to echocardiogram after BSCPA (mo) | TR | | *Z* value tricuspid annulus | | Valve morphology | | | RV function | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before BSCPA | After BSCPA | Before BSCPA | After BSCPA | Anterior leaflet | Septal leaflet | Posterior leaflet | Before BSCPA | After BSCPA |
| 2 | 5 | 17.87 | III* | I | 2.21 | 0.32 | Normal | Normal | Normal | Moderately reduced | Normal |
| 2 | 10 | 49.48 | III* | 0 | 2.79 | NA | Prolapse | Restriction | Normal | Normal | Mildly reduced |
| 2 | 42 | 23.57 | III* | II | 0.95 | 0.18 | Normal | Restriction | Normal | Normal | Normal |
| 2 | 51 | 12.85 | III* | II | 1.96 | 0.99 | Normal | Prolapse | Normal | Normal | Normal |
| 2 | 52 | 15.77 | III* | II | 1.41 | 0.82 | Prolapse | Restriction | Normal | Normal | Normal |
| 2 | 74 | 11.25 | III* | II | 1.13 | 1.43 | Prolapse | Restriction | Prolapse | Normal | Normal |
| 2 | 78 | 0.69 | III* | II | 2.44 | 1.55 | Prolapse | Normal | Normal | Normal | Normal |
| 3 | 2 | 21.80 | III* | IV* | NA | 2.35 | Normal | Normal | Normal | Mildly reduced | Mildly reduced |
| 3 | 39 | 11.80 | III* | IV* | 1.75 | 1.04 | Prolapse, ruptured chordae | Restriction | Normal | Mildly reduced | Normal |
| 3 | 70 | 0.36 | III* | III* | 0.60 | –0.14 | Prolapse | Restriction | Normal | Normal | Normal |
| 3 | 77 | 8.36 | III* | III* | 2.36 | 1.63 | Normal | Restriction | Normal | Normal | Normal |
| 3 | 8 | 18.52 | II | IV* | NA | 1.76 | Prolapse, perforation | Restriction | Normal | Normal | Normal |
| 3 | 18 | 15.05 | II | III* | NA | 1.24 | Normal | Restriction | Normal | Normal | Mildly reduced |
| 3 | 23 | 57.21 | II | III* | 1.33 | 2.46 | Prolapse | Restriction | Normal | Normal | Normal |
| 3 | 24 | 44.07 | II | IV* | 0.87 | 0.75 | Prolapse | Normal | Normal | Normal | Normal |
| 3 | 35 | 32.75 | II | III* | 2.17 | 0.25 | Prolapse | Restriction | Normal | Normal | Normal |
| 3 | 47 | 30.23 | II | IV* | 1.65 | 1.88 | Prolapse | Restriction | Normal | Normal | Normal |
| 3 | 82† | 1.90 | I | III* | NA | 2.00 | Normal | Normal | Normal | Normal | Moderately reduced |

*BSCPA,* Bidirectional superior cavopulmonary anastomosis; *TR,* tricuspid regurgitation; *NA,* data not available. *Significant TR. †Died before total cavopulmonary connection.

follow-up echocardiograms revealed an unchanged percentage of patients with significant TR after BSCPA. Considering the individual patients, almost one half exhibited no change in the grade of TR and 40% exhibited a change of ±1 grade (ie, postoperative grade of TR was 1 grade more or 1 grade less than the preoperative grade of TR). The patients with significant TR preoperatively had a larger annulus than the rest of the series, and, similarly, the patients with significant TR postoperatively had a larger TV annulus than those with nonsignificant TR postoperatively. These findings have demonstrated the importance of TV annulus dilation in the pathophysiology of TR. It is known that the morphology of the TV varies in patients with HLHS.[11] In our study, the most common pathology of TV leaflets in the patients with significant TR was restriction of the septal leaflet and prolapse of the anterior leaflet; the leaflets were only seldom described as normal.

### TV Annulus

Before BSCPA, patients with HLHS have a faster rate of tricuspid annulus growth than the patients with normal, biventricular hearts.[6] Our data have indirectly confirmed this finding, because the TV annulus in our series was larger than in the normal population. BSCPA diverts the blood flow from the superior vena cava to the lungs and, therefore, reduces the volume load of the systemic RV.[5] Although this has been shown even in patients in whom an additional source of pulmonary blood flow has been preserved after BSCPA,[11] it is important to note that, as we previously reported, we never leave any additional blood flow when performing BSCPA.[12] Seliem and colleagues[13] reported that the RV end-diastolic volume decreases by 33% after BSCPA. In our patient population, the mean *Z* value of the TV annulus decreased significantly after BSCPA in all patients without no significant TR postoperatively. This is in accordance with work by Michelfelder and colleagues,[6] who showed that the decreased ventricular volume after BSCPA normalizes the rate of tricuspid annulus growth. However, in the present study, the relative size of the TV annulus did not change after BSCPA in the patients with significant TR postoperatively. Significant TR after BSCPA leads to high preload and might neutralize RV remodeling.

### Tricuspid Annular Plane Systolic Excursion

To achieve a better understanding of the changes in the RV after BSCPA, we examined the TAPSE. The measurement of

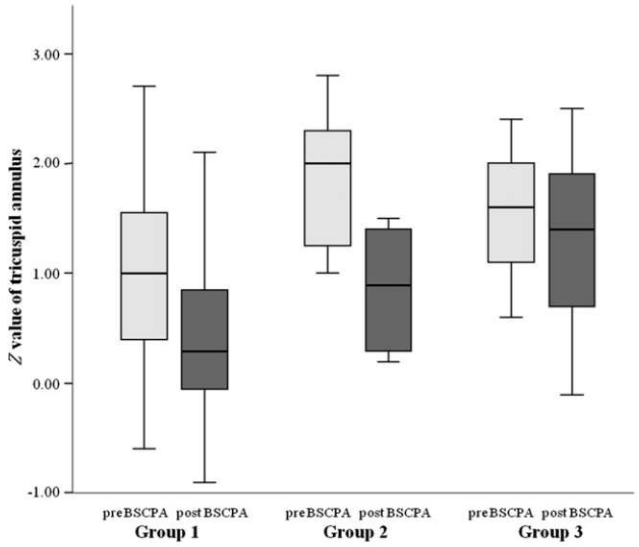


**FIGURE 2.** *Z* value of tricuspid annulus, before and after bidirectional superior cavopulmonary anastomosis *(BSCPA)*. See text for details of patient groups. *Upper* and *lower box* plot margins represent interquartile range; *middle bar* indicates median; vertical lines represent data within 1.5-fold interquartile range above the third and below the first quartile.

TAPSE has been described as easily reproducible and reported to have high specificity and negative predictive power for detecting abnormal RV systolic function in adult patients.[14] The largest TAPSE values are found in the context of normal RV and LV systolic function.[15] Few reports have addressed TAPSE in children with congenital heart disease. Because it has been shown that TAPSE is affected by increasing age, we evaluated TAPSE indexed to age, as suggested by Koestenberger and colleague.[9] Nii and colleagues[16] have suggested that TV annular dynamics are different in patients with HLHS because of a lack of interaction with the left ventricle. All the patients in our series had reduced TAPSE compared with the normal values for the corresponding age group, both before and after BSCPA, although most had normal RV function. In the patients with nonsignificant TR, TAPSE was significantly reduced after BSCPA. In the presence of significant TR, no operation-related change in TAPSE was noted. This suggests that TAPSE is directly related to RV preload status: before BSCPA (with the aortopulmonary, modified Blalock-Taussig, or Sano shunt), the preload and TAPSE levels are greater than the post-BSCPA levels. RV preload and TAPSE only remain high after BSCPA in patients with significant TR. It is also of note that TAPSE is a volume-dependent parameter. Owing to the larger difference between the systolic and diastolic RV volumes, the TAPSE is greater when TR is present.

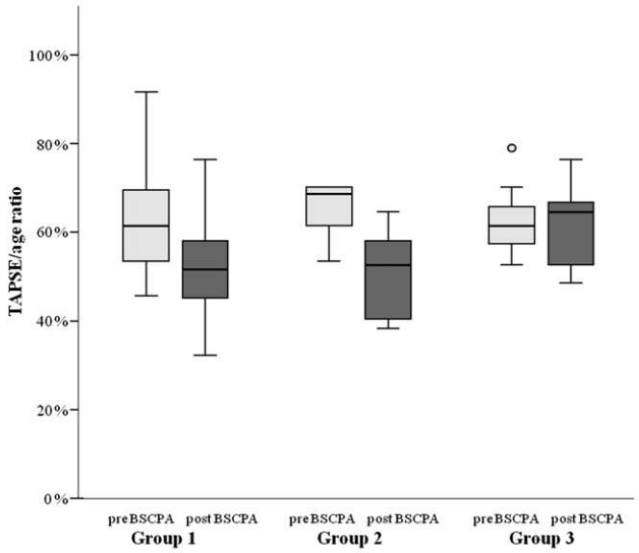


**FIGURE 3.** Tricuspid annular plane systolic excursion *(TAPSE)*/age ratio before and after bidirectional superior cavopulmonary anastomosis *(BSCPA);* 100% depicts mean expected value of normal population. See text for details of patient groups. *Upper* and *lower box* plot margins represent interquartile range; *middle bar* indicates median; vertical lines represent data within 1.5-fold interquartile range above third and below first quartile; data 1.5 interquartile range higher than third quartile were considered outliers and shown with circles.

## RV Function

The effect of volume overload on the function of the systemic RV in patients with HLHS has been extensively investigated, leading to the current consensus of favoring early unloading.[17] Hansen and colleagues[10] described a deterioration of RV function after BSCPA. In their study, the follow-up echocardiograms were done 2 weeks after BSCPA, and the RV dysfunction might have been caused by the effects of the cardiopulmonary bypass. In our study, the prevalence of reduced RV function was also greater after BSCPA. Most of the patients who had reduced RV function postoperatively had a normally functioning ventricle before the operation. Because the interval between BSCPA and the second echocardiogram for each of these patients was more than 8 weeks, the postoperative RV dysfunction was unlikely to be a transient effect due to some element of the operation. A partial explanation for this finding is that morphologically the RV is required to support the systemic circulation in patients with HLHS. However, because the mechanisms of how hypoplasia of the left heart affects the function of the systemic RV in patients with HLHS are complex and not completely understood, additional detailed investigation of the morphology and function of the systemic RV are needed to clarify this phenomenon.

## Potential Clinical Implications

A recent study by Elmi and colleagues[2] showed that approximately one quarter of all HLHS survivors will have undergone surgical TV procedures within the first 10 years of life. They noted that most of the TV interventions are performed in the early years of childhood but that a certain percentage of children require valve surgery at a later date, after

completion of univentricular palliation.[2] The surgical strategy is individual, depends on the specific valve morphology, and includes variations in annuloplasty (De Vega, posterior leaflet obliteration) and leaflet/chordal reconstruction. Several publications have reported good outcomes for surgical repair of the systemic TV in patients with HLHS.[3,18-20] However, the correct timing for valvuloplasty in patients with a single ventricle is still debated. A recent study by Dinh and colleagues[20] showed an early success rate of 71% after tricuspid repair, with most patients maintaining good valve function during the follow-up period. Although younger patients had worse early outcomes, no significant differences were seen in age or weight at tricuspid repair between the success and failure groups at the late outcome point.[20] Some studies have suggested that regurgitation at the atrioventricular valve in patients with univentricular heart might improve after BSCPA without concomitant valvuloplasty,[7] although others have argued the opposite and suggest a TV repair at BSCPA if more than moderate regurgitation is present.[10] Our data have shown that most of the patients with HLHS will experience a reduction in the relative size of the TV annulus after BSCPA. However, this remodeling of the RV does not lead to an improvement in TR. The patients with significant TR after BSCPA had a larger TV annulus than those with nonsignificant TR. A possible explanation might be that significant TR after BSCPA neutralizes RV remodeling or, vice versa, when RV remodeling does not lead to a reduction of the annulus, significant TR remains after BSCPA.

It can therefore be assumed that, without surgical intervention, the grade of TR present at BSCPA will remain unchanged until completion of the univentricular palliation, which usually occurs 1 to 2 years after BSCPA. During this time, significant TR might have a detrimental effect on the long-term function of the RV. Taking all this into account, together with the good results after tricuspid valvuloplasty, which have been reported even in younger children with HLHS, it can be postulated that, although an individual approach to each patient is necessary, in the patients with significant TR (moderate and severe), TV repair should be considered at the time of BSCPA.

### Study Limitations

The present study was retrospective, and the echocardiograms were obtained from the hospital archive. Thus, it was not possible to measure all the desired parameters from the available echocardiographic loops. Although the study group was relatively large, the number of the patients with significant TR was small. This might have limited the value of the statistical evaluation of the groups.

## CONCLUSIONS

Unloading of the right ventricle by BSCPA in patients with HLHS promotes the remodeling of the systemic RV, which leads to a decrease in the relative size of the TV annulus. However, this remodeling of the RV does not improve the degree of TR. In the presence of significant TR, TV repair should be considered at the time of BSCPA.

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## Discussion

**Dr Shunji Sano** *(Okayama, Japan).* Just to clarify, the partial cavopulmonary connection (PCPC) means the bidirectional Glenn or hemi-Fontan?

**Dr Kasnar-Samprec.** We almost always performed a bidirectional Glenn.

**Dr Pedo del Nido** *(Boston, Mass).* First, congratulations for a very timely study. I think all of us are very interested in the tricuspid valve in this particular patient group, and your information is actually going to be very useful for decision-making. I also want to thank you for sending me the manuscript with plenty of time.

I would like to try to delve slightly deeper into some of the information that you provided and to really try to understand your recommendation, because I agree with you, but I think the rationale still needs to be discussed.

The first question I have for you is that if we focus on your group 2, the patients who had improvement in their volume size and tricuspid valve annulus with only the PCPC, if I understand it correctly, the vast majority of those patients, had some degree of significant TR, and they improved on their own without any intervention on the tricuspid valve. Is that correct?

**Dr Kasnar-Samprec.** Yes, 7 of the patients did.

**Dr del Nido.** If that is the case, can you tell me something about the surgical factors that might have contributed to that. In other words, how many of those patients had shunts versus right ventricle to pulmonary artery conduits and what was their Qp/Qs at the time they underwent the stage 2 procedure?

**Dr Kasnar-Samprec.** These are the patients operated on between 2001 and 2010. In the early years, we mostly used aortopulmonary shunts or modified Blalock-Taussig shunts. Later, we were using the right ventricle to pulmonary artery conduits as often as possible. Studying the 3 groups separately, no significant difference was seen between the number of Sano shunts and the number of other shunts used. So, the groups were approximately the same. We had approximately one quarter of the aortopulmonary shunts or modified Blalock-Taussig shunts in all groups.

**Dr del Nido.** But you have no information about the Qp/Qs?

**Dr Kasnar-Samprec.** No. Unfortunately, I have no information on the Qp/Qs.

**Dr del Nido.** I am sure they all had catheters place, so I think that information might be available.

**Dr Kasnar-Samprec.** Yes, definitely.

**Dr del Nido.** The other question I had, and really it is more of a concern, and that is that you had a median follow-up of 17 months, which is great, because it is important to know what happens within that period, but your range was from 7 days to 57 months.

**Dr Kasnar-Samprec.** Yes.

**Dr del Nido.** My question is: Clearly your technique evolved during those 10 years, were there differences in the follow-up period for the 3 different groups?

**Dr Kasnar-Samprec.** No.

**Dr del Nido.** No differences?

**Dr Kasnar-Samprec.** No, there were no differences. We had, all together, 9 patients who underwent follow-up echocardiography between 7 and 28 days postoperatively. Actually, only 1 patient at day 7, the next 4 patients at approximately day 14, and the rest later.

We sometimes operate on patients who travel from other countries to our institution, and we did not have all the necessary data for our study, so we could not reevaluate more recent echocardiograms. However, the median time for each group was approximately 17 months. It was 17 months for group 1, 16 for group 2, and 18 for group 3. The mean values were also approximately the same.

**Dr del Nido.** Okay. Thank you.

My next question relates to your recommendation, which is that one should consider tricuspid valve repair if the patient has more than mild tricuspid regurgitation, moderate or severe, at the stage 2 procedure, which gets at the predictive value of your study. You have 2 groups, 1 group that got better on its own, which was group 2, and 1 group that did not. What would you recommend as a procedure that would cover both of those groups?

**Dr Kasnar-Samprec.** When we started the study, we clearly first looked at whether there is something which we could use to determine directly before the PCPC, yes, this patient definitely needs tricuspid surgery; or no, this patient definitely does not. Our data unfortunately did not show that. So, the 2 graphs I showed are actually based on the knowledge of what happened after the PCPC.

It would clearly be very easy to say, yes, in group 3, the annulus will not change, so we should do an annuloplasty. In group 2, we do not have to anything. However, this is unfortunately not the case. At the time when we are planning the PCPC, we cannot predict which patient will have an improvement of significant TR or which will develop significant TR. So, this is definitely a very difficult question.

**Dr del Nido.** The flip side of that coin is that if you are suggesting annuloplasty, the annulus size in all your patients was within 2 standard deviations of normal. So, they were all normal. Thus, reducing the annulus might or might not help very much at all. Also, in fact, the worst group, group 3, had no change in valve annulus, and it was normal. So, it begs the question.

**Dr Kasnar-Samprec.** It was normal; however, it was larger than in the normal population, just as in all of other patients before PCPC.

**Dr del Nido.** Usually within plus or minus 2 standard deviations is considered normal. All your patients, if I understand it correctly, were within that range.

The other question that I have is that if you consider the Single Ventricle Reconstruction trial, which was a large trial, they have a very similar experience. The incidence of more than mild tricuspid regurgitation was slightly greater, at stage 2, it was about 18%. However, if you look 1 year later, or 14 months later, the incidence was the same, independent of what was done to those children.

The question is: Were those the same children? Also, I think what your study is showing is that there are different groups. Some children definitely improve by just having the volume load removed and then there are those who do not. But we still do not have a very good predictor of which children will or will not improve.

**Dr Kasnar-Samprec.** Definitely, we do not have a good predictor. What I did not show here is that we described the morphology of the TV in all patients who had significant TR. Usually the anterior leaflet was larger, the septal leaflet somewhat smaller, and so on. So, there are things a surgeon can do, except make the annulus smaller. There were only 2 cases in which our cardiologist described the leaflets as completely normal. All other patients had something that could have theoretically been addressed at the PCPC.

**Dr J. William Gaynor** *(Philadelphia, Pa).* I enjoyed your paper, too, and I agree this is a very important topic. I also agree with Pedro that knowing the degree of volume overload estimated by the Qp/Qs is very important.

Two other questions, and I might have missed this. Were these echocardiographic measurements taken from reports or were the echocardiograms read again for this study?

**Dr Kasnar-Samprec.** They were read again. A single experienced observer looked at every echocardiogram again.

**Dr Gaynor.** Then second, 1 issue we found that affects the severity of TR in these children is any degree of residual arch obstruction. Even fairly mild degrees can cause them to have TR. Thus, sometimes relief of the arch obstruction can result in an improvement in the TR. So, do you have any data about any residual arch obstruction in any of these children? Had any of them undergone balloon dilation or other surgical interventions?

**Dr Kasnar-Samprec.** Definitely. We perform an angiogram directly before PCPC. I do not have the data regarding the Qp/Qs here. However, when our cardiologists find a residual gradient in the aorta, they perform balloon angioplasty. The patients who underwent angioplasty before PCPC, they are always controlled afterward as well. Most of the patients in this study had no gradient or had a relatively mild gradient. I could say that this should not be an issue in this study.

**Dr Gaynor.** But I think it is an important item to check.

**Dr Kasnar-Samprec.** Definitely.

**Dr Glen Van Arsdell** *(Toronto, Ontario, Canada).* It is an interesting topic and a difficult topic. One of the factors that is becoming clear is that we do not volume unload as much as we think. Magnetic resonance imaging data have shown, when magnetic resonance imaging is done later, the patients have a Qp/Qs of about 0.8.

It also is clear that many of them have morphologic problems that you considered. So, I wondered in the subset of patients with improvement, did you look to see whether their valve had a morphologic problem or whether with the temporary volume unloading that occurs, it was the patients with annular dilation who improved? Were you able to differentiate on that basis who might show improvement?

**Dr Kasnar-Samprec.** We studied all the patients who had, at any time, significant TR, we described extra the morphology of the valves. However, the morphology of the valves was not significantly different among the groups.

**Dr Gerhard Ziemer** *(Chicago, Ill).* I might have missed the information; however, to judge these outcomes, one should know something about the intraoperative course, such as surgery performed on bypass, off bypass, and if on bypass, how long were the bypass times. Because this could have some effect on the myocardial and pulmonary function. You did not present this.

**Dr Kasnar-Samprec.** Do you mean during the Norwood operation?

**Dr Ziemer.** No, during this operation, the Glenn anastomosis, did you do it on bypass or off bypass?

**Dr Kasnar-Samprec.** We did all of them on bypass.

**Dr Ziemer.** Well, if you did all on bypass, it would be interesting to know whether those who did worse by any measure, had a longer bypass run and just were worse because of that. This is just information one would like to have, I think.

**Dr Kasnar-Samprec.** Thank you for the suggestion.

# PAPER II

# Recoarctation After the Norwood I Procedure for Hypoplastic Left Heart Syndrome: Incidence, Risk Factors, and Treatment Options

Julie Cleuziou, MD, Jelena Kasnar-Samprec, MD, Jürgen Hörer, MD, PhD, Andreas Eicken, MD, PhD, Rüdiger Lange, MD, PhD, and Christian Schreiber, MD, PhD

Departments of Cardiovascular Surgery and Pediatric Cardiology and Congenital Heart Disease, German Heart Center Munich, Technische Universität München, Munich, Germany

*Background.* **Early survival after the Norwood I procedure has improved over the years, but subsequent morbidity is not yet well assessed. The aim of this study was to review the incidence of recoarctation, evaluate risk factors, and analyze treatment options.**

*Methods.* **We reviewed the medical records of 124 consecutive patients with hypoplastic left heart syndrome (HLHS) who underwent the Norwood I procedure. Reconstruction of the aortic arch was performed in a standardized manner, removing all visible ductal tissue and enlarging the distal anastomosis with a Y incision into the descending aorta. Angiographic assessment with measurement of the peak gradient across the aortic arch was performed before the second stage was performed.**

*Results.* **Recoarctation of the aorta was documented in 13 patients (13.4%) at a mean time of 6.4 ± 5 months after the Norwood procedure. One patient died before the recoarctation could be treated. Right ventricular function was good in all except 1 patient at the time of diagnosis. Ten patients underwent 16 percutaneous balloon angioplasties, and 2 patients underwent operative enlargement of the neoaorta. The pretreatment peak gradient of 24.1 ± 16 mm Hg (10–64 mm Hg) across the aortic arch was significantly reduced to 6.3 ± 4 mm Hg (0–14 mm Hg) after angioplasty or operation ($p = 0.003$). There were no procedure-related deaths. No risk factor for recoarctation could be identified.**

*Conclusions.* **A standardized surgical technique for reconstruction of the aorta leads to a low recoarctation rate. Balloon angioplasty can be performed in the majority of patients before the second-stage procedure.**

**(Ann Thorac Surg 2013;95:935–40)**


Early mortality after the Norwood I procedure for hypoplastic left heart syndrome (HLHS) has decreased in the past decade and is about 22% [1]. As the number of survivors increase, the focus turns to more long-term morbidity. One of the surgical challenges of the Norwood procedure is the reconstruction of the hypoplastic aortic arch, which bears the risk of recurrent obstruction. The rate of recoarctation of the aorta is reported to be between 10% and 36% [2, 3]. Possible consequences are ventricular dysfunction and tricuspid regurgitation, which lead to further morbidity and subsequent mortality. Reasons for the development of a recoarctation cannot yet be demonstrated, although some authors postulate that the patch material used might be an important factor [4, 5].

Our aim was to evaluate our surgical strategy for avoiding recoarctation in patients with HLHS undergoing the Norwood I procedure. Furthermore, we aimed at evaluating possible risk factors contributing to recoarctation and analyzing treatment options.

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Address correspondence to Dr Cleuziou, Department of Cardiovascular Surgery, German Heart Centre Munich, Lazarettstrasse 36, D-80636, Munich, Germany; e-mail: cleuziou@dhm.mhn.de.

## Patients and Methods

### *Patients*

This study was approved by the Ethics Committee of the Technical University of Munich.

We reviewed the data of all patients with HLHS undergoing a Norwood I procedure at the German Heart Center Munich between May 2000 and December 2010. The diagnosis of HLHS was made by echocardiography and was characterized as a hypoplastic aortic arch, aortic atresia or stenosis, mitral atresia or stenosis, and hypoplastic left ventricle. The study population consisted of patients who survived until the second-stage procedure—bidirectional partial cavopulmonary anastomosis (BCPA). Data were obtained by review of medical records and angiograms. Patient factors analyzed were age, weight, sex, and diameter of the ascending aorta at the time of the Norwood procedure. Operative characteristics included the technique used to reconstruct the aortic arch and the patch material.

Before BCPA, patients routinely underwent angiography with contrast injection into the ascending aorta and measurement of the pressure gradient between the ascending and the descending aorta. Once a recoarctation was diagnosed, it was dilated during the same session. Review of the angiograms composed the assessment of


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the first onset of a recoarctation and the monitoring of the result after angioplasty. For analyzing the pressure gradients, we included only patients in whom measurements were available at least 2 different times after the Norwood procedure.

Based on the guidelines of the European Society of Cardiology [6], a balloon angioplasty was performed if the following findings were present: pressure gradient of greater than 20 mm Hg and aortic narrowing of more than 50%.

In the particular setting of a functional single ventricle, our policy is not to accept any aortic obstruction. If the aorta showed a narrowing but the gradient was less than 20 mm Hg, we proceeded with an angioplasty. When a catheter-based intervention was not possible, surgical relief of the recoarctation was undertaken at the time of BCPA.

### *Norwood Procedure*

The modified Norwood procedure was performed based on the description of Mosca and colleagues [7]. After a median sternotomy, cardiopulmonary bypass was established with cannulation of the main pulmonary trunk and bicaval cannulation. While the patient was cooling to a core temperature of 20°C, the atrial septum was completely resected through a right atriotomy. The heart was arrested with cold crystalloid cardioplegia, and with the patient in deep hypothermic arrest, the duct was ligated and the pulmonary trunk divided at the height of the pulmonary bifurcation. After resection of the visible ductal tissue, leaving the posterior wall, the aortic arch was opened along its inner curvature down to the sinotubular junction of the ascending aorta. The ascending aorta was then connected to the proximal pulmonary trunk. The descending aorta was enlarged using a Y incision (Fig 1), and the aortic arch was reconstructed using a patch. The choice of patch material depended on surgeon discretion and availability. The pulmonary artery bifurcation was closed with a patch, and while rewarming the patient, a systemic-to-pulmonary or a right ventricle–to–pulmonary artery shunt was placed. The shunt used was again decided at the surgeon's discretion. A total of 5 surgeons performed the Norwood operation at our institution over the years.

### *Statistical Methods*

Descriptive statistics are described as frequencies and percentages for categorical variables and as medians with ranges or means with standard deviation for continuous variables. The Kaplan-Meier method was used to estimate the freedom from recoarctation after the Norwood procedure. Risk factors for the development of a recoarctation were analyzed by the $X^2$ or Fisher's exact test for categorical variables and *t* tests for continuous variables. Statistical analysis was performed using SPSS statistical software, version 19 (IBM Corp, Armonk, NY).

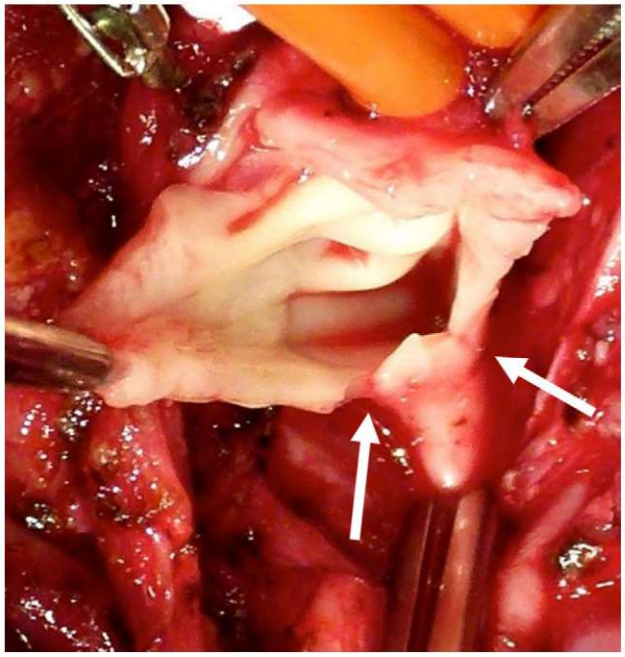

*Fig 1. The Norwood procedure. Operative view of the Y incision (arrows) enlarging the descending aorta.*

## Results

A total of 124 consecutive patients underwent the Norwood I procedure. Median age at time of the Norwood procedure was 8 days (1–26 days) and median weight was 3,200 g (1,800–4,410 g). The mean diameter of the ascending aorta was 3.5 ± 1.6 mm. Patient characteristics and surgical data are summarized in Table 1. Hospital mortality was 15% (n = 19), and 8 patients (6.4%) died before BCPA. In the patients who died before they underwent BCPA, postoperative echocardiography and in some cases angiography could rule out the presence of a recoarctation. The remaining 97 patients represented the study population.

Recoarctation was diagnosed in 13 patients (13.4%). Freedom from recoarctation was 89.5% ± 3.3%, 88.2% ± 3.5%, and 84.9% ± 4.1% at 6 months, 12 months, and 10 years, respectively (Fig 2). For reconstruction of the aorta in these patients, patch materials included a homograft in 11 patients, autologous pericardium in 1 patient, and a cryopreserved femoral vein in 1 patient. Right ventricular function was good in all except 1 patient. One patient with a recoarctation and a pressure gradient of 23 mm Hg died of irreversible cyanosis 1 day before surgical relief of the recoarctation and BCPA could be undertaken. Because the patient had good myocardial function and the primary symptom was cyanosis, we assume that the cause of death was not related to the recoarctation.

Recoarctation was treated in 12 patients: 10 had balloon angioplasty and 2 underwent surgical relief of the obstruction (Fig 3). Relief of the recoarctation was performed at a mean time of 6.4 ± 5 months after the Norwood I procedure. Angiographic data with measurements of the pressure gradient at least 2 different times

*Table 1. Patient Characteristics and Surgical Data for 124 Patients Undergoing the Norwood Procedure*

| Variable | n (%) |
|---|---|
| Age | |
| <7 d | 33 (27%) |
| 7–13 d | 78 (63%) |
| ≥14 d | 13 (10%) |
| Sex | |
| Male | 89 (72%) |
| Weight | |
| <3 kg | 40 (32%) |
| ≥3 kg | 84 (68%) |
| Aortic diameter (mean in mm ± SD) | 3.5 ± 1.6 |
| Aortic arch reconstruction: patch material used | |
| Pulmonary homograft | 97 (78%) |
| Autologous pericardium (treated with glutaraldehyde) | 16 (13%) |
| None | 2 (1.6%) |
| Bovine jugular vein | 4 (3.2%) |
| Polytetrafluoroethylene | 1 (1%) |
| Human femoral vein | 4 (3.2%) |

SD = standard deviation.

after the Norwood I procedure were available for 73 patients. The mean pressure gradient in patients with recoarctation was 24.1 ± 16 mm Hg compared with 2.2 ± 5.3 mm Hg in patients without recoarctation ($p = 0.001$). After intervention, the pressure gradient was reduced to 6.3 ± 4 mm Hg ($p = 0.003$) (Fig 4). Fig 5 shows the angiograms of a patient before and after balloon angioplasty. No patient died after relief of recoarctation. There were no intervention-related complications such as aneurysm formation or dissection of the aorta. Six patients required a further intervention during a mean follow-up time of 3.4 ± 2.8 years. Two patients with recoarctation had second operations on the aortic arch at the time of BCPA. Both patients had their Norwood I procedure in the early era of balloon angioplasty, and an interventional approach was estimated as not feasible. The patch material used for reconstructing the aorta in both patients was taken from a pulmonary homograft. At reoperation, intraoperative findings showed that the obstruction resulted from remaining ductal tissue in 1 patient. The reason for the recoarctation in the other patient remains unclear, the obstruction being 5 mm proximal to the anastomotic site.

In the univariate analysis, no morphologic or surgical characteristics showed an influence on the development of a recoarctation (Table 2). The patch material used to reconstruct the aortic arch especially had no significant impact on recoarctation.

## Comment

A known complication after the Norwood I procedure is the development of recoarctation, with rates reported to be between 10% and 36% [2, 3]. In our study population, the incidence was 13%. In the context of a functional single ventricle, a consecutive obstruction can lead to ventricular dysfunction and tricuspid regurgitation with detrimental outcome. In a postmortem study, the cause of death resulting from recoarctation after the Norwood I procedure was found to be 14% [8].

Several options for reconstructing the aortic arch, in terms of patch material used and anastomosing techniques, have been described [9, 10]. Searching for a mechanism that may be responsible for the development of recoarctation, different possibilities have been discussed. Machii and associates [11] suggested that recoarctation is caused by ductal tissue remaining in the aorta. This is in accordance with other authors who recommend complete elimination of all ductal tissue during the Norwood I procedure [4, 5]. However as Machii and colleagues demonstrated, ductal tissue might expand out onto the inner wall of the aorta and may be detectable only by microscopy. Therefore in a recent postmortem study, which revealed that 33% of patients show inadequate resection of the ductal tissue located distal to the patch material after the Norwood I procedure, the authors recommended extending the patch further into the descending aorta [12]. It is also our aim to remove all visible ductal tissue during the Norwood I procedure, but we might miss some of it, as was the case in 1 patient who underwent a second operation. Additionally, we widen our anastomosis through a Y incision. We think that this magnification leads to a lower rate of recoarctation. Another suggestion for improving the surgical results is the "interdigitating technique," in which an incision is made in the anterior and posterior wall of

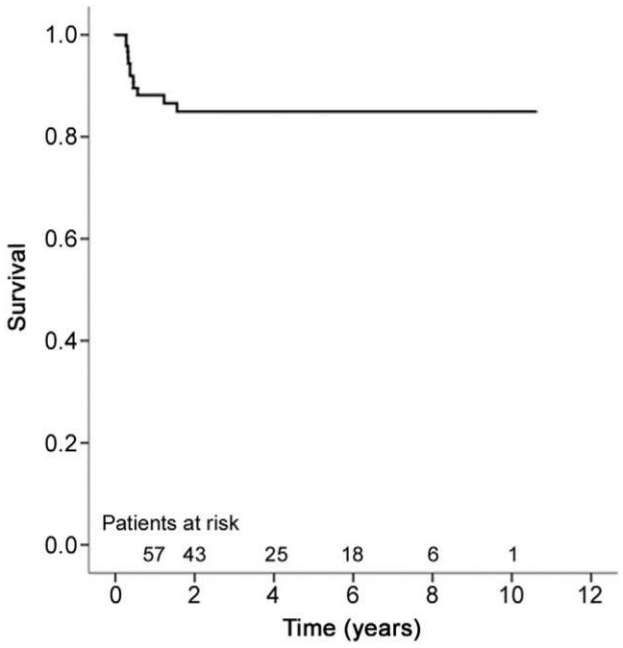


*Fig 2. Kaplan-Meier analysis. Freedom from intervention for recoarctation of the aorta in 97 patients after the Norwood I procedure.*

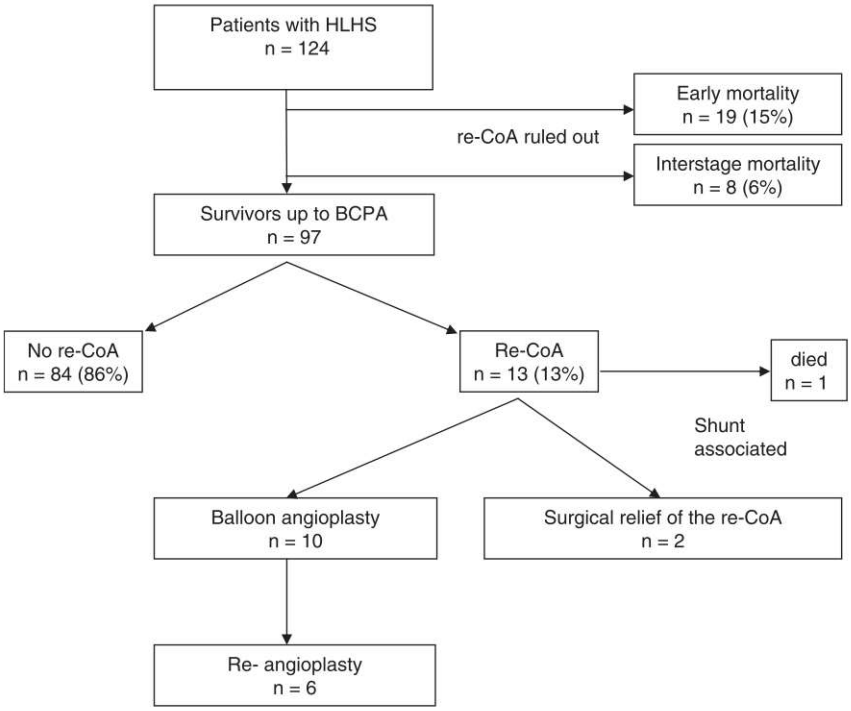


*Fig 3. Outcome in patients with hypoplastic left heart syndrome (HLHS) after the Norwood I procedure. (BCPA = bidirectional cavopulmonary anastomosis; re-CoA = recoarctation.)*

the descending aorta [9]. With this technique, these authors claim to have resolved the problem of recoarctation. However this technique implies a complete transection of the aorta, which means more dissection of the descending aorta; this is technically more demanding and might take more time [13]. We do not think that a complete transection of the aorta, which will mean a longer duration of total circulatory arrest, is necessary to keep a low rate of recoarctation after the Norwood I procedure.

Besides the surgical technique, the patch material used for reconstruction of the aortic arch may be a potential cause of recurrent obstruction. Ashcraft and colleagues [4] showed a trend but no significance for more recoarctations in patients in whom bovine pericardium was used. In another study of 210 patients, autologous pericardium was found to be a protective factor against recoarctation development [5]. Although we used different patch materials in our cohort, none was associated with a higher incidence for the development of recoarctation.

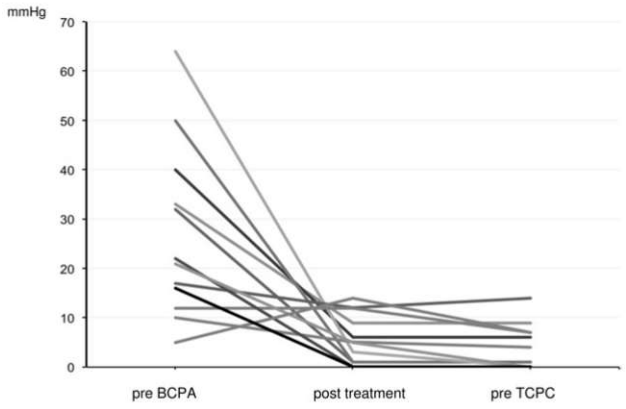


*Fig 4. Pressure gradients across the aortic arch in 12 patients with recoarctation after the Norwood I procedure, before bidirectional cavopulmonary anastomosis (BCPA), after treatment, and before total cavopulmonary connection (TCPC).*

Especially in the setting of a functional single ventricle, a downstream obstruction may impair the ventricular function in the long term. According to the European Society of Cardiology guidelines, there is an indication for intervention in a coarctation of the aorta if the noninvasive pressure gradient is greater than 20 mm Hg, if there is upper limb hypertension, or if there is evidence of left ventricular hypertrophy or a pathologic blood pressure response on exercise [6]. These guidelines are recommended for adults with congenital heart defects and may not be transferable to patients with HLHS. Our policy for intervening in recoarctation after the Norwood I procedure is more stringent and is reflected in our results. Four patients presented with preintervention status of a gradient less than 20 mm Hg, but there was visual narrowing of the aorta. All our patients undergo angiography before BCPA, with the possibility of proceeding with a balloon angioplasty during the same session. We advocate timely treatment of a recoarctation before BCPA because it can lead to recovery of impaired ventricular function [14].

Treatment options include balloon angioplasty or surgical relief of the recoarctation. Although balloon angioplasty is considered the therapy of choice in many centers [3, 15, 16], it is not exempt from complications. Besides a treatment failure of 8% [17] to 29% [16],

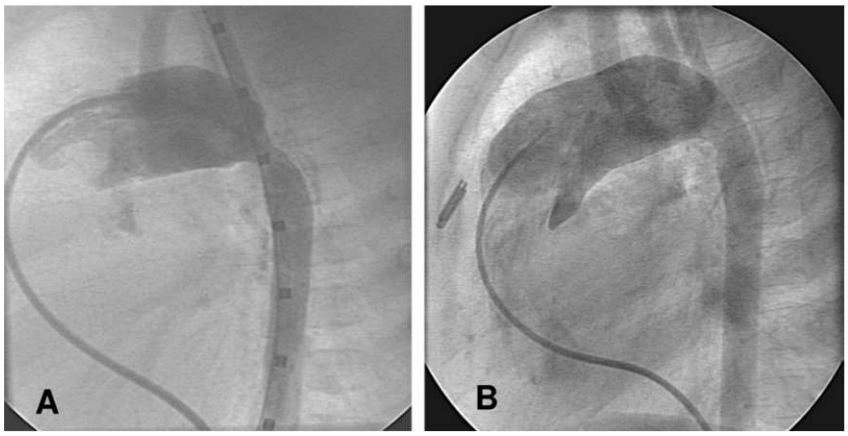


*Fig 5. Angiographic image of a patient (A) before and (B) after balloon angioplasty of a recoarctation after the Norwood I procedure.*



morbidity includes the need for resuscitation [15] and temporary extravasation [16]. In our patient cohort, we did not observe early complications after balloon angioplasty, but the redilatation rate was high, with 6 patients requiring a second intervention before total cavopulmonary connection (TCPC). This high rate of repeated balloon angioplasty is consistent with other results found in the literature [15, 17]. Compared with these results, the 2 patients in whom we performed surgical relief of the recoarctation had no complications in the long term. We would still opt for a balloon angioplasty the first time because we had no procedure-related complications. However in the setting of complex morphologic characteristics, the surgical option needs to be discussed and might be a valid alternative to interventional therapy.

### *Conclusions*

A low rate of recoarctation after the Norwood procedure can be achieved through complete resection of ductal tissue and additional enlargement of the distal aortic anastomosis. An obstruction in the setting of a single ventricle should not be tolerated. A balloon angioplasty seems to be the best choice to achieve this goal. It can be performed at the time of preoperative angiography before BCPA, but reintervention before TCPC is occasionally required.

*Table 2. Risk Factor Analysis for 97 Patients With and Without a Recoarctation After the Norwood Procedure*

| Variable | With Recoarctation (n = 12) | Without Recoarctation (n = 85) | *p* Value |
|---|---|---|---|
| Weight (g) | 3,100 ± 397 | 3,220 ± 475 | 0.4 |
| Age (d) | 9.2 ± 3.2 | 8.9 ± 3.8 | 0.8 |
| Sex (male) | 9 | 65 | 1.0 |
| Patch material | | | |
| Homograft | 10 | 67 | 1.0 |
| Pericardial tissue | 1 | 10 | 1.0 |
| Human femoral vein | 1 | 3 | 0.4 |
| Bovine jugular vein | 0 | 3 | 1.0 |
| None | 0 | 2 | 1.0 |
| Aortic diameter (mm) | 3.5 ± 1.2 | 3.5 ± 1.6 | 0.9 |

### *Study Limitations*

The design of this study was retrospective and the study period was 10 years. Changes in preoperative, operative, and postoperative management may have affected the outcome measurements in a way not covered by our analysis. Furthermore, the surgical technique was not compared with another technique and therefore we cannot prove that this technique is better than another.

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# Notice From the American Board of Thoracic Surgery

The 2012 Part I (written) examination was held on Monday, November 19, 2012. To be admissible to the Part II (oral) examination, a candidate must have successfully completed the Part I (written) examination.

A candidate applying for admission to the certifying examination must fulfill all the requirements of the Board in force at the time the application is received.

Please address all communications to the American Board of Thoracic Surgery, 633 N St. Clair St, Suite 2320, Chicago, IL 60611; telephone: (312) 202-5900; fax: (312) 202-5960; e-mail: info@abts.org.

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# CURRICULUM VITAE

| | |
|---|---|
| Name | Dr. Jelena Pabst von Ohain |
| Geburtsname | Kašnar-Šamprec |
| Geburtsdatum | 01. November 1977 |
| Geburtsort | Zagreb, Kroatien |
| Familienstand | verheiratet, 3 Kinder |

**Aktuelle Tätigkeit**

Leitende Oberärztin

Sektion für Chirurgie angeborener Herzfehler und Kinderherzchirurgie, LMU Klinikum

Telefon: +49 89 440077277

E-Mail: j.pabst.von.ohain@med.uni-muenchen.de

**Studium**

2002 – 2009 Postdiplomstudium an der Fakultät der Naturwissenschaften der Universität von Zagreb

1996 - 2002 Medizinische Fakultät der Universität von Zagreb

**Werdegang**

seit 10/2019 **LMU Klinikum**

Sektion für Chirurgie angeborener Herzfehler und Kinderherzchirurgie

2007 – 2019 **Deutsches Herzzentrum München**

Klinik für Chirurgie angeborener Herzfehler und Kinderherzchirurgie,

Klinik für Herz- und Gefäßchirurgie

2004 – 2007 **Kinderkrankenhaus, Zagreb, Kroatien**

Klinik für Kinderchirurgie

**Qualifikationen**

| | |
|---|---|
| 2015, 2020: | Zertifikat Chirurgie angeborener Herzfehler<br>*Deutsche Gesellschaft für Thorax-, Herz- und Gefäßchirurgie* |
| 2014 | Fachärztin für Herzchirurgie<br>*Bayerische Landesärztekammer* |
| 2013, 2021 | Prüfärztin in klinischen Prüfungen nach AMG und MPG<br>*Trainingszentrum Management klinischer Studien* |
| 2009 | PhD: "Mechanismus von Antikrebs-Aktivitäten von N-sulfonylcitozyne Derivaten"<br>*Fakultät der Naturwissenschaften der Universität von Zagreb* |
| 2006 | Zertifikat ECFMG/USMLE,<br>*Educational Commission for Foreign Medical Graduates, USA* |
| 2003 | Lizenz als Doktor der Medizin<br>*Kroatische Ärztekammer* |
| 2002 | Dr. med. (Univ. Zagreb)<br>*Medizinische Fakultät der Universität von Zagreb* |

**Mitgliedschaften**

European Congenital Heart Surgeons Association

Deutsche Gesellschaft für Thorax-, Herz- und Gefäßchirurgie

Deutsche Gesellschaft für Pädiatrische Kardiologie und Angeborene Herzfehler

Bayerische Landesärztekammer

## Publications

### First, last and shared authorship

Pabst von Ohain J, Tonino E, Kaemmerer H, Cleuziou J, Ewert P, Lange R, Hörer J. German Heart Centre Munich - 45 Years of Surgery in Adults with Congenital Heart Defects: From Primary Corrections of Septal Defects and Coarctation to Complex Reoperations. Cardiovasc Diagn Ther. 2021 Apr;11(2):492-502.

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* equally contributing authors

## Co-authorship

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