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Clinical Research

Change in Pulmonary Arteries after Modified Blalock-Taussig Shunt Procedure: Analysis Based on Computed Tomography

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See Commentary page 240.

Background: Although the modified Blalock-Taussig shunt remains the mainstay method of palliation for augmenting pulmonary blood flow in various congenital heart diseases, the shunt must be carefully designed to achieve the best outcomes. This study investigated the effect of shunt configuration on pulmonary artery growth and growth discrepancy.
Methods: Twenty patients with successful modified Blalock-Taussig shunt takedown were analyzed. Pulmonary artery and shunt characteristics were obtained using computed tomography scans. Differences in the baseline and follow-up diameter ratios and growth in the ipsilateral and contralateral arteries were calculated. The angle between the shunt and pulmonary artery, as well as the distance from the main pulmonary artery bifurcation, were measured. Correlations between pulmonary arteries and shunt configurations were analyzed.
Results: The median interval time between shunt placement and takedown was 154.5 days (interquartile range, 113.25–276.25 days). Follow-up values of the ipsilateral-to-contralateral pulmonary artery diameter ratio showed no significant correlation with the shunt angle (ρ=0.429, p=0.126) or distance (ρ=0.110, p=0.645). The shunt angle and distance from the main pulmonary bifurcation showed no significant correlation (ρ=-0.373, p=0.189). Pulmonary artery growth was negatively correlated with shunt angle (ipsilateral, ρ=-0.565 and p=0.035; contralateral, ρ=-0.578 and p=0.030), but not with distance (ipsilateral, ρ=-0.065 and p=0.786; contralateral, ρ=-0.130 and p=0.586).
Conclusion: Shunt configuration had no significant effect on growth imbalance. The angle and distance of the shunt showed no significant correlation with each other. A more vertical shunt was associated with significant pulmonary artery growth. We suggest a more vertical graft design for improved pulmonary artery growth.

Keywords: Modified Blalock-Taussig shunt, Shunt angle, Shunt configuration, Pulmonary artery growth, Computed tomography

Introduction

The Blalock-Taussig shunt (BTS) was first introduced in 1945 to provide pulmonary blood flow in patients with compromised pulmonary circulation. It has been proven safe and highly effective in achieving pulmonary artery (PA) growth [1,2]. By using an artificial graft, surgeons were able to modify it and gain easier surgical access to reduce complications arising from the cessation of the main blood supply to the ipsilateral arm [3]. The modified BTS allowed surgeons more freedom in designing the shunt configuration with respect to the PA, since the distance and angle at which it was placed on the PA was relatively easy to manipulate. It is now the most used surgical technique for palliation [4,5]. Over the years, surgical indications for BTS have widened from tetralogy of Fallot to single-ventricle diseases due to its safety and efficacy [6].

Although excellent outcomes have been achieved in terms of PA growth, survival, and patency rates, studies of how shunt configuration affects hemodynamic outcomes are scarce [7,8]. It may seem logical to place the shunt as vertically and centrally as possible (i.e., an inverted T-shape located at the main pulmonary artery [MPA] bifurcation) to achieve even PA growth and blood flow. However, it is not uncommon in pediatric patients to have underlying conditions that result in uneven PA sizes and flow distribution, which can later require repeated percutaneous or surgical interventions after the BTS. Optimal outcomes can be achieved in the BTS procedure with careful designing of the shunt configuration along with close intraoperative and perioperative monitoring [9]. This study aimed to determine which structural configurations most effectively impact PA growth and blood flow to provide an optimal graft design for the BTS.

Methods

Patients and surgical procedures

A total of 33 patients who underwent the BTS procedure between January 2013 and October 2022 were retrospectively analyzed. Only patients who had received 2 computed tomography (CT) scans between the BTS procedure and the takedown operation (the next-stage operation) were included in the study. CT scans were performed before takedown of the BTS in all but 1 case, and that patient received a follow-up scan 4 days after the operation. The patient also underwent concomitant MPA division during the BTS operation with a bidirectional cavopulmonary shunt (Glenn shunt), which was anastomosed at the previous BTS division site. No concomitant angioplasty was performed during the Glenn procedure. Given the short interval between the next-stage operation and the CT scan, as well as the fact that there was minimal surgical intervention during the next-stage operation, the patient was included for analysis. In cases where the initial CT scan was performed before the BTS, shunt configurations were measured using the follow-up images. If any sequential angioplasty or intervention was performed between the BTS and takedown, and no images were taken afterwards, the patient was excluded. The initial and follow-up PA diameters, the angle between the shunt and PA, and the distance of the shunt from the PA bifurcation were measured. PA diameters were all measured at the first lobar bifurcation.

All operative procedures were performed by 2 surgeons who used the same surgical method, which is described below. A 3.5-mm polytetrafluoroethylene (PTFE) (GORE-TEX Vascular Grafts; W. L. Gore and Associates Inc., Flagstaff, AZ, USA) vascular graft is most widely used for neonates and infants since a 3-mm diameter PTFE graft is currently unavailable in Korea. Typically, the BTS procedure is performed via median sternotomy, and we do not hesitate to use cardiopulmonary bypass when the patient's vital signs are unstable or the PA is small and requires angioplasty. The graft is beveled at both ends, whenever necessary, to minimize tension and kinking of the native arteries. The innominate artery is dissected and mobilized extensively to beyond the bifurcation of the subclavian and common carotid arteries. We attempt to anastomose the vascular graft as distally as possible, to the proximal portion of the subclavian artery directly after the innominate artery. This is because a 3.5-mm graft could lead to pulmonary overflow and result in low cardiac output and cardiac arrest, particularly in infants and neonates weighing less than 3 kg. For the shunt insertion site at the PA, we aim to select the mid-portion of the confluent PA, as close to the MPA as possible. This is to ensure even distribution of pulmonary blood flow. If the patent ductus arteriosus (PDA) is located ipsilateral to where the shunt graft is placed (for patients with a left aortic arch and a right PDA or vice versa), all ductal tissue is removed, and this area is used for shunt anastomosis under cardiopulmonary bypass support. We believe that pulmonary overflow is difficult to control using extracorporeal methods outside the surgical field. This contrasts with adjustments for hypoxia, which can be relatively well manipulated with mechanical ventilation, volume control, and active lung care.

Measurement and analysis

All measurements were made by a single analyst using the hospital's own picture archiving and communication system (PACS) software (INFINITT PACS; INFINITT Healthcare Co. Ltd., Seoul, Korea). As previously mentioned, all diameters were measured at the first lobar bifurcation of the PAs. The parallel distance between the shunt anastomosis site and the MPA bifurcation was also measured. Perpendicular planes were drawn from each respective location, and the distance between the 2 planes was measured. The PA diameters and shunt distances were measured from the axial CT view (Fig. 1A, B). Since the study cohort included both left and right BTS procedures, the laterality of the PAs was defined as ipsilateral or contralateral in relation to the shunt. The direction of the shunt distance was also toward the laterality of the BTS. This was done to ease calculations and improve understanding by eliminating negative values in shunt distances.

Coronal CT views were used to measure the angle between the shunt graft and the PA. Since the BTS and PAs are curved structures, the angle was measured where the

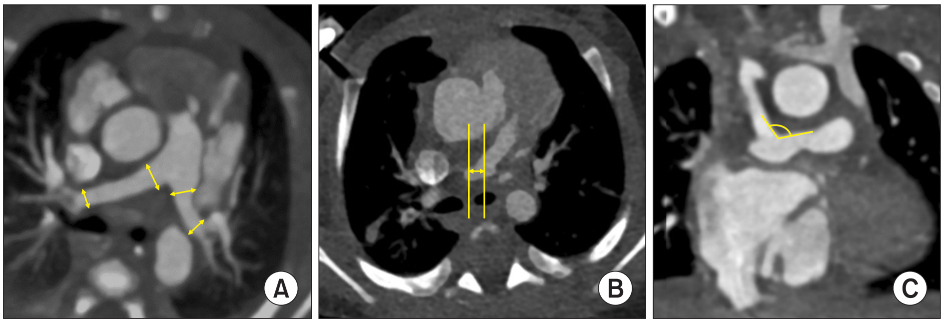

Fig. 1. (A) The right pulmonary artery (RPA) and left pulmonary artery (LPA) diameters just before the first lobar bifurcation were measured using an axial computed tomography (CT) view. The maximum diameters of the RPA and LPA were also measured. (B) The distance between the perpendicular planes at the main pulmonary artery (MPA) bifurcation and the center of the shunt was measured using an axial CT view. (C) The angle between the modified Blalock-Taussig shunt and MPA was measured using a coronal CT view. The lines are tangents of each structure.

tangent lines of both structures met (Fig. 1C). Again, to consider both left and right BTSs, the medial border of the shunt and the adjacent PA were used for analysis.

All units of distance and length were measured in millimeters (mm) and angles in degrees. In patients who had their MPA divided or had pulmonary atresia, the stump of the divided or atretic MPA was considered the bifurcation point. Although PA diameters were measured in all 20 patients, shunt angles were only available in 14 patients. In addition, the ipsilateral-to-contralateral (I/C) ratio of the PA diameter was calculated to represent any size discrepancy.

The Z-scores of the PA diameters were calculated using the weight and height (body surface area [BSA]) of the patients measured on the day the CT scans were performed. The difference in Z-scores between the initial and follow-up CT was calculated to represent the actual size-for-BSA growth of the PAs.

Statistics and ethics

The Wilcoxon signed-rank test was used to compare and identify whether there was an actual increase in the PA diameter Z-scores and I/C ratio. The Spearman correlation coefficient (ρ) was used to identify any associations between shunt configuration values and PA values. The study was approved by the Institutional Review Board of Seoul National University Hospital (approval no., H-2305-106-1432). The requirement for informed consent from individual patients was omitted because of the retrospective design of this study.

Results

Clinical outcomes

Among the 33 patients, 6 patients died before receiving the next stage operation due to septic shock, shunt overflow, and PA thrombosis. An additional 6 patients were excluded for a lack of appropriate CT scans. One patient was excluded because the BTS procedure was not performed at our hospital, and the surgical details were unavailable.

Preoperative patient demographics, including the initial diagnoses, are listed in Table 1. Twelve patients were male and 9 weighed less than 2.5 kg at birth. Seven patients were born preterm. All but 4 of the BTS grafts were 3.5 mm. Three patients received a 4-mm graft for the following reasons. One received a new left-sided BTS due to significant stenosis of the right pulmonary artery (RPA) after an initial right-sided 3.5-mm shunt. The second had the initial 3-mm graft revised due to progressive hypoxia and the last patient was too large (4.8 kg) to receive a 3.5-mm shunt. One patient with total anomalous pulmonary venous return received several reoperations due to insufficient PA growth. The initial shunt was 3 mm, but the shunt was replaced twice over a period of 3 years and 2 months to finally end with a 6-mm graft. The reoperations were due to progressive pulmonary vein stenosis and hypoxia. The final 6 mm graft was in place for 16 months and the patient continued to receive percutaneous interventions on the graft due to persistent stenosis until receiving a bidirectional cavopulmonary shunt (Glenn shunt) operation. There were 2 additional cases that required revision of the BTS. One patient received a 3.5-mm shunt 11 days after an initial 3.0-mm shunt because of persisting hypoxia, which improved immediately after revision. Another patient received reoperation to reposition the origin more proximally towards the aorta. The patient experienced persistent hypoxia due to insufficient blood flow to the PAs. A review of the preoperative and postoperative CT scans revealed increased PA sizes with improved oxygenation levels. The details of patients who underwent BTS revision are summarized in Table 2.

Other operative characteristics, including the next-stage operations, are listed in Table 3. There were 17 right-sided and 3 left-sided BTS procedures. All patients received ductus arteriosus division during the BTS procedure, and all next-stage operations included takedown of the BTS. Of the 12 patients who were possible candidates, only 11 successfully underwent biventricular repair. One patient with a double outlet right ventricle, pulmonary atresia, and ventricular septal defect received a Glenn shunt due to a hypoplastic right ventricle and very small PA annulus. Eight and 13 patients received concomitant PA angioplasty during the BTS and next-stage operations, respectively. Details of the target PA are also described in Table 3. The median interval between the BTS and next-stage operations was 154.5 days (interquartile range [IQR], 113.25–276.25 days).

Table 1. Baseline characteristics of patients who underwent modified BTS procedures (2013–2022)

Characteristic	Value
No. of patients	20
Baseline characteristics	
Male	12 (60)
Birth weight (kg)	2.66 (2.04–3.52)
Low birth weight (<2.5 kg)	9 (45)
Gestational age (wk)	37.93 (35.82–38.96)
Prematurity (<37 wk)	7 (35)
Chromosomal abnormalities	2 (10)
Operative characteristics	
Weight at BTS (kg)	3.5 (3.3–4.05)
Age at BTS (day)	43.5 (17.5–78)
Diagnosis	
Functional single ventricle	5 (25)
Pulmonary atresia with IVS	1 (5)
Pulmonary atresia with VSD	9 (45)
Tetralogy of Fallot	3 (15)
Hypoplastic left heart syndrome	2 (10)
Dominant ventricle morphology	
Left	5 (25)
Right	4 (20)
Biventricular	11 (55)

Values are presented as number, number (%), or median (interquartile range).
BTS, Blalock-Taussig shunt; IVS, intact ventricular septum; VSD, ventricular septal defect.

Analysis of pulmonary artery growth according to Blalock-Taussig shunt configuration

Only the latest BTS of each patient was used in the analysis. If the patient had received a right BTS that was later replaced by a left BTS due to complications, only measurements of the new BTS graft were considered. Patient details at the time of the CT scans are summarized in Table 4, including PA diameters, Z-scores, and growth. The median CT follow-up period was 144 days (IQR, 120–253 days). The initial median diameters of the ipsilateral and contralateral PAs (PA_I and PA_C) were 4.49 mm (IQR, 3.73–5.40 mm) and 4.10 mm (IQR, 3.89–4.83 mm), respectively. The follow-up median diameters of the PA_I and PA_C were 6.32 mm (IQR, 5.13–7.21 mm) and 5.84 mm (IQR, 4.32–7.63 mm), respectively. The follow-up values of the PA_I-to-PA_C size ratio showed a weak positive correlation with the shunt angle ($\rho=0.429$, $p=0.126$). The PA_I-to-PA_C size ratio also showed a weak positive correlation with the distance

Table 2. Details of patients who received modified BTS revision (n=5)

Patient	Age at initial BTS (day)	Size and location (mm)	Interval until revision (day)	Size and location (mm)	Reason for revision	Interval until revision (day)	Size and location (mm)	Reason for revision	Interval until takedown (day)
A	1	3.5, Right	124	4.0, Right	Persistent hypoxia	1,023	6.0, Right	Persistent hypoxia, insufficient PA growth	551
B	31	3.5, Right	18	3.5, Right	Persistent hypoxia				186
C	41	3.0, Right	11	3.5, Right	Persistent hypoxia				374
D	45	3.5, Right	33	4.0, Left	RPA stenosis				45
E	51	3.0, Left	91	4.0, Left	Shunt occlusion				666

BTS, Blalock-Taussig shunt; PA, pulmonary artery; RPA, right pulmonary artery.

Table 3. Operative characteristics, including the initial modified BTS operation, the next-stage operation, and concomitant angioplasty, at a single center in Korea (2013–2022)

Characteristic	Value
Shunt characteristics (n=20)	
Size (mm)	
3.5	16 (80)
4	3 (15)
6	1 (5)
Left shunt	3 (15)
Angle at PA insertion (°)	116.45 (103.60–128.98)
Distance from MPA bifurcation (mm)	5.97 (2.63–8.87)
Concomitant angioplasty[a]	8 (40)
Ipsilateral (n=8)	
MPA flap	1 (5)
Patch angioplasty	8 (40)
Contralateral (n=6)	
MPA flap	2 (10)
Patch angioplasty	4 (20)
MPA treatment (n=6)	
Division	4 (20)
Patch angioplasty	1 (5)
Interval between BTS and next-stage operation (day)	154.5 (113.25–276.25)
Next-stage operation (n=20)	
Bilateral cavopulmonary shunt	9 (45)
Rastelli operation	9 (45)
Tetralogy of Fallot total correction	1 (5)
DORV repair without RV-PA conduit	1 (5)
Concomitant angioplasty[a]	13 (65)
Contralateral (n=9)	
MPA flap	2 (10)
Patch angioplasty	7 (35)
Ipsilateral (n=6)	
MPA flap	2 (10)
Patch angioplasty	4 (20)
MPA (n=3)	
Patch angioplasty	3 (15)

Values are presented as number (%) or median (interquartile range).
BTS, Blalock-Taussig shunt; PA, pulmonary artery; MPA, main pulmonary artery; DORV, double outlet right ventricle; RV, right ventricle.
[a] Concomitant angioplasty was either patch angioplasty or MPA rotational flap angioplasty. There were 8 and 13 cases of angioplasty during the initial BTS operation and next-stage operation, respectively.

of the shunt from MPA bifurcation (ρ=0.110, p=0.645). An increasing shunt angle, as well as shunt distance, seemed to result in a greater discrepancy between the PA diameters (greater PA_I-to-PA_C size ratio), but these correlations lacked statistical significance. The mean PA_I-to-PA_C size ratios at the initial and follow-up analyses were 1.10±0.33 and 1.20±0.35, respectively, but the change in the PA_I-to-PA_C size ratio was not statistically significant (p=0.433).

The median increase of the PA_I and PA_C diameters were 2.05 mm (IQR, 0.85–2.66 mm) and 0.99 mm (IQR, 0.20–2.68 mm), respectively. The median difference in the increase (PA_I-to-PA_C) was 0.27 mm (IQR, -0.58 to 1.97 mm). The PA_I seemed to grow larger, but this trend did not show statistical significance (p=0.313). The initial and follow-up median Z-scores of the PA_I were -0.36 (IQR, -1.19 to 0.26) and 0.29 (IQR, -0.96 to 1.04), respectively. The initial and follow-up median Z-scores of the PA_C were -0.50 (IQR, -0.73 to 0.41) and 0.07 (IQR, -1.73 to 1.05), respectively. Although the Z-scores of the ipsilateral and contralateral PAs increased numerically during the follow-up period, this change was not statistically significant (PA_I, p=0.108; PA_C, p=0.550). The mean Z-scores for the right and left PAs (RPA and LPA) at the initial CT for each diagnosis are summarized in Supplementary Table 1.

Table 4. Comparison of the initial and follow-up computed tomography scans in patients who underwent modified Blalock-Taussig shunt operations (n=20)

Characteristic	Value
Follow-up period (day)	144 (120 to 253)
Initial scan	
Age (day)	33.5 (18.25 to 80.50)
Weight (kg)	3.42 (3.09 to 4.08)
BSA (m^2)	0.21 (0.20 to 0.23)
Nakata index (mm^2/m^2)	149.88 (118.83 to 194.6)
Ipsilateral artery diameter (mm)	4.59 (3.73 to 5.40)
Contralateral artery diameter (mm)	4.10 (3.89 to 4.83)
Ipsilateral artery Z-score	-0.36 (-1.19 to 0.26)
Contralateral artery Z-score	-0.50 (-0.73 to 0.41)
I/C ratio	1.10±0.33
Follow-up scan	
Age (day)	196.5 (126.25 to 321.25)
Weight (kg)	6.95 (6.16 to 8.10)
BSA (m^2)	0.33 (0.32 to 0.38)
Nakata index (mm^2/m^2)	173.54 (148.02 to 220.60)
Ipsilateral artery diameter (mm)	6.32 (5.13 to 7.21)
Contralateral artery diameter (mm)	5.84 (4.32 to 7.63)
Ipsilateral artery Z-score	0.29 (-0.96 to 1.04)
Contralateral artery Z-score	0.07 (-1.73 to 1.05)
I/C ratio	1.20±0.35
Ipsilateral artery growth (mm)[a)]	2.05 (0.85 to 2.66)
Contralateral artery growth (mm)[a)]	0.99 (0.20 to 2.68)
Growth difference (mm)[b)]	0.27 (-0.58 to 1.97)

Values are presented as median (interquartile range) or mean±standard deviation.

BSA, body surface area; PA, pulmonary artery; I/C ratio, ipsilateral-to-contralateral pulmonary artery diameter ratio.

[a)] Growth denotes the difference in PA diameter during the follow-up period. [b)] Growth difference refers to the difference between ipsilateral and contralateral PA growth.

Further analysis was performed to identify correlations between PA growth and the configuration of the BTS. The angle between the shunt and the PA showed a negative correlation with the distance from the MPA bifurcation (ρ=-0.373, p=0.189). Although this result was not statistically significant (Fig. 2), it could be inferred that a more centrally located shunt was also more slanted. PA growth (difference in PA$_I$ and PA$_C$ Z-scores) within the follow-up period showed a significant negative correlation with the shunt angle (PA$_I$, ρ=-0.565 and p=0.035; PA$_C$, ρ=-0.578 and p=0.030) (Fig. 3). In other words, a vertical shunt yielded growth of both PAs. The distance of the BTS from the MPA bifurcation showed weak negative correlations with PA$_I$ and PA$_C$ growth (Fig. 4). A greater distance between the BTS and the bifurcation was associated with less growth in either PA (PA$_I$, ρ=-0.065 and p=0.786; PA$_C$, ρ=-0.130 and p=0.586). Although growth failure in the contralateral artery seemed more common, the difference was not statistically significant.

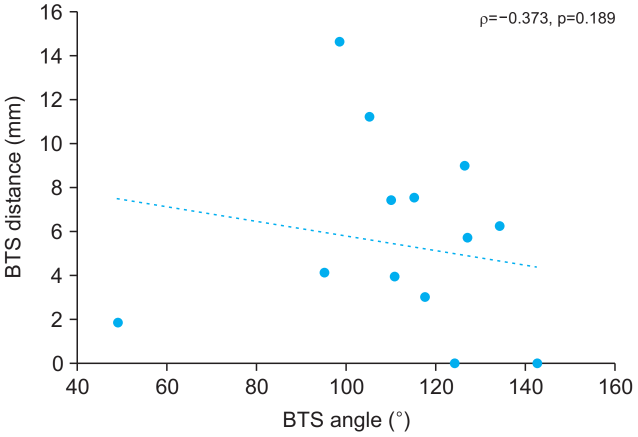

Fig. 2. Scatter plot showing a negative correlation between the Blalock-Taussig shunt (BTS) distance from the main pulmonary artery (MPA) bifurcation (y-axis: BTS distance) and the BTS angle with the MPA (x-axis: BTS angle) (ρ=-0.373, p=0.189). The shunt angles of 14 patients were analyzed. ρ, Spearman correlation coefficient; p, statistical significance.

Discussion

Previous attempts to investigate optimal blood flow through the BTS from the systemic artery to the PA have either used computer simulations of flow dynamics or clinical patient data. In a 3-dimensional simulation, Song et al. [10] found that the best fluid passage was identified when the BTS was placed peripherally. In other words, a greater shunt distance in either direction led to increased pulmonary blood flow [10]. Yet, our results showed bilateral growth failure with increasing shunt distance (Fig. 4). This may be because better fluid passage does not necessarily mean PA growth. The authors also suggested less pulmonary interference as a reason for increased flow. However, some of our patients had received MPA division, and other factors such as pulmonary hypertension and mechanical ventilation status were not included in the simulated models. Another study reported that a vertical BTS led to increased total PA blood flow [11]. Our study showed similar bilateral PA growth failure with increasing shunt angle. Regardless, our results warrant further real-world and real-patient analysis of how to configure the BTS so that it provides optimal PA growth.

It is well known that the patient's postoperative volume status and lung condition have a significant impact on BTS blood flow. In addition to these patient factors, the BTS configuration may also have a significant impact on the

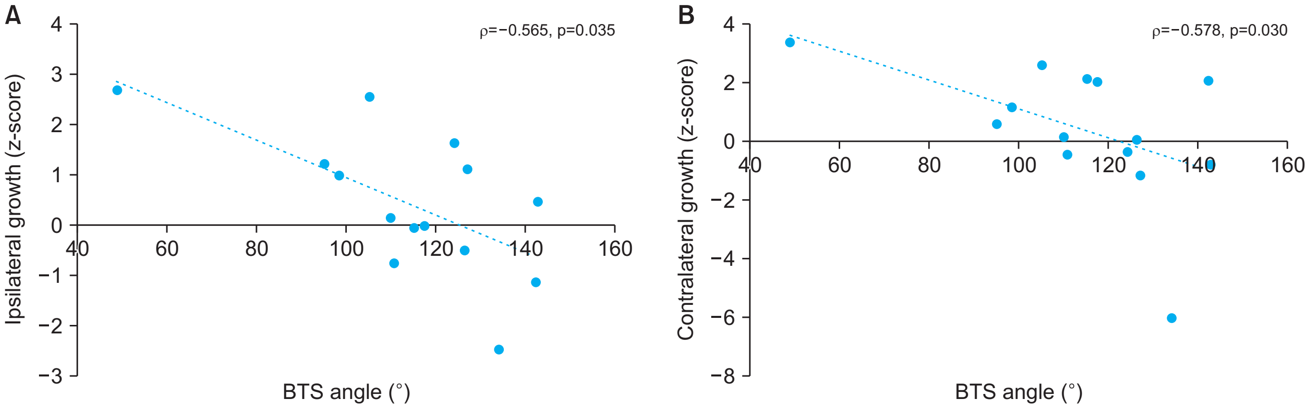

Fig. 3. (A) Scatter plot of the Blalock-Taussig shunt (BTS) angle (with the main pulmonary artery [MPA]) and ipsilateral pulmonary artery (PA) growth (Z-score difference) (ρ=-0.565, p=0.035). (B) Scatter plot of the BTS angle (with the MPA) and contralateral PA growth (Z-score difference) (ρ=-0.578, p=0.030). The shunt angles of 14 patients were analyzed. ρ, Spearman correlation coefficient; p, statistical significance.

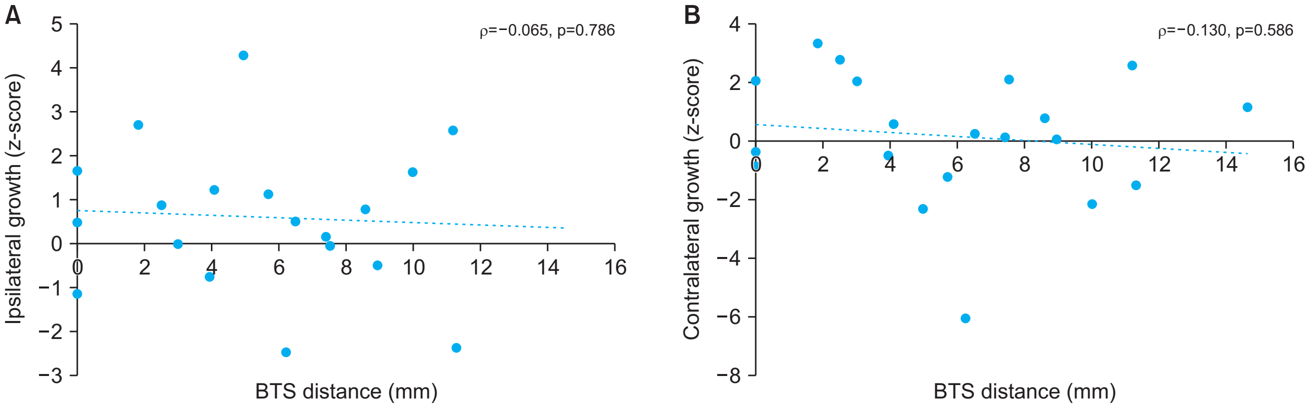

Fig. 4. (A) Scatter plot of the Blalock-Taussig shunt (BTS) distance (from the main pulmonary artery [MPA] bifurcation) and ipsilateral pulmonary artery (PA) growth (Z-score difference) (ρ=-0.065, p=0.786). (B) BTS distance (from the MPA bifurcation) and contralateral PA growth (Z-score difference) (ρ=-0.130, p=0.586). ρ, Spearman correlation coefficient; p, statistical significance.

patient's hemodynamic status [12]. Therefore, the BTS should be precisely tailored, avoiding pulling or kinking of the native systemic and pulmonary vessels for stable blood flow to the lungs. Once the BTS is properly designed, we can more easily predict and manage the patient's hemodynamic status by adjusting other patient-related variables. Even and adequate BTS flow to both PA branches is crucial not only in the immediate postoperative period but also in the late postoperative period, especially in single ventricle patients. In patients where the BTS is replaced by a venous drainage system such as a bidirectional Glenn shunt, the pressure and flow may not be sufficient to achieve adequate PA growth.

Our initial hypothesis was that a smoother angle between the BTS and the native vessels (both systemic and PAs) would result in a less turbulent and steady blood flow, leading to improved PA growth. We have encountered several cases where the endothelium opposite the shunt site was thickened with fibrotic change caused by jet flow from the BTS. The second hypothesis was that the insertion site of the BTS graft at the PA (shunt shift) would influence the size difference between the LPA and RPA arising from uneven PA blood flow distribution. Therefore, we sought to find the best angle and location of the BTS for even PA growth.

The results of our study failed to corroborate our first hypothesis. There was a significant correlation between the shunt angle and PA growth (diameter Z-score), showing that an obtuse angle with the central PA was associated with smaller bilateral PAs. A more slanted BTS resulted in an overall decrease in blood flow and bilateral growth failure, implying that a more vertical graft would lead to bilateral PA growth. Furthermore, from the weak correlation between shunt angle and distance (from the MPA bifurcation), we can infer that the shunts inserted closer to the center had more slanted configurations. Since we follow a policy to place the BTS as centrally as possible, it follows that the shunt will be more slanted and beveled to reach the center. This could eventually lead to an increased total graft length with a consequent decrease in velocity and blood flow to the PAs. The lengths of individual BTS grafts included in the study were not available. Further prospective studies with more sophisticated shunt designs, such as sigmoidal shapes that can be located centrally while maintaining a vertical angle, may be another approach.

Regarding the imbalance in growth, a stronger association was expected at the insertion site of the shunt, rather than at the origin. Therefore, we analyzed the I/C diameter ratio from the follow-up CT results after BTS placement. Although weak and not statistically significant, our cohort showed an increased I/C ratio with the shunt angle. However, these results were only implications derived from the size ratios and not actual growth and may have resulted from our small cohort size as well as the lack of statistical significance. To assess actual PA growth, we acquired diameter Z-score values.

Generally, the PA anastomosis of a modified BTS is made perpendicularly below the systemic artery anastomosis site. However, some patients have a stenotic portion in the pulmonary confluence, particularly associated with the insertion site of the ductus arteriosus. Therefore, we removed ductal tissue as much as possible and attempted to anastomose the pulmonary end of the BTS at the mid-portion of the pulmonary confluence or at the ductus arteriosus insertion site. During the Glenn procedure, we also anastomosed the superior vena cava as centrally as possible, under the same hypothesis that it will provide equal blood flow distribution to both PA branches. Further investigation of the second phase of PA growth after the next-stage operation may help in understanding the postoperative changes in such patients.

Although shunt size and surgical expertise are established factors in general postoperative outcomes, studies on the effect of graft configuration are scarce in the current literature. As mentioned previously, there have been a few studies using computer simulation and modeling. Although the measured dimensions in the present study were 2-dimensional, the strength of the study was that all data were collected from real patient results. To analyze growing, dynamic, 3-dimensional structures accurately is nearly impossible in a retrospective manner, given only 2-dimensional screenshot images. Nevertheless, we believe that we have brought the best out of what was available.

Limitations

This study had a few limitations. Primarily, the large variation in baseline patient characteristics, especially primary diagnoses, was due to its retrospective design. Although most patients (16 out of 20) received a graft of the same size (3.5 mm), our study did not include graft size for analysis. Shunt size was selected according to the patient's PA size and body weight, as well as concurrent conditions such as pulmonary overflow and hypoxia. The operative findings were limited to available documentation, and any details on tailoring of the BTS were gathered from imaging studies only. This was a single-center study with a very small cohort (n=20), and further large-scale prospective trials are warranted. Nevertheless, the modified BTS has a long positive history and consistent surgical procedures were used by the 2 surgeons participating in the study. We believe our results will compare closely with other centers worldwide. Due to the palliative nature of the BTS procedure, it is impossible to analyze the long-term effects of the graft configurations. However, there were 5 cases of BTS revision in this study and, although some patients received immediate intervention, some had their previous shunt for several months before replacement. The effect of the initial BTS in these cases could have been masked over the years until the final takedown.

Conclusion

The BTS graft configuration had a significant effect on the growth and size of the PAs. A more vertically designed BTS resulted in bilateral PA growth. Regarding growth discrepancy, weak correlations were found between the PA_I-to-PA_C diameter ratio and the shunt configurations, but they were not statistically significant. To achieve adequate PA growth, we suggest that the BTS graft be anastomosed to the MPA bifurcation as vertically as possible.

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Conflict of interest

No potential conflict of interest relevant to this article was reported.

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Supplementary materials

Supplementary materials can be found via https://doi.org/10.5090/jcs.23.128. **Supplementary Table 1.** The initial RPA and LPA Z-scores for each diagnostic group undergoing BTS surgery.

References

1. Blalock A, Taussig HB. Landmark article May 19, 1945: The surgical treatment of malformations of the heart in which there is pulmonary stenosis or pulmonary atresia. By Alfred Blalock and Helen B. Taussig. JAMA 1984;251:2123-38. https://doi.org/10.1001/jama.251.16.2123
2. Stewart S, Alexson C, Manning J, Oakes D, Eberly SW. Long-term palliation with the classic Blalock-Taussig shunt. J Thorac Cardiovasc Surg 1988;96:117-21. https://doi.org/10.1016/s0022-5223(19)35304-8
3. Yuan SM, Shinfeld A, Raanani E. The Blalock-Taussig shunt. J Card Surg 2009;24:101-8. https://doi.org/10.1111/j.1540-8191.2008.00758.x
4. Guyton RA, Owens JE, Waumett JD, Dooley KJ, Hatcher CR Jr, Williams WH. The Blalock-Taussig shunt: low risk, effective palliation, and pulmonary artery growth. J Thorac Cardiovasc Surg 1983;85:917-22. https://doi.org/10.1016/S0022-5223(19)37483-5
5. Lamberti JJ, Carlisle J, Waldman JD, et al. Systemic-pulmonary shunts in infants and children: early and late results. J Thorac Cardiovasc Surg 1984;88:76-81. https://doi.org/10.1016/S0022-5223(19)38389-8
6. Williams JA, Bansal AK, Kim BJ, et al. Two thousand Blalock-Taussig shunts: a six-decade experience. Ann Thorac Surg 2007;84:2070-5. https://doi.org/10.1016/j.athoracsur.2007.06.067
7. Gold JP, Violaris K, Engle MA, et al. A five-year clinical experience with 112 Blalock-Taussig shunts. J Card Surg 1993;8:9-17. https://doi.org/10.1111/j.1540-8191.1993.tb00571.x
8. Al Jubair KA, Al Fagih MR, Al Jarallah AS, et al. Results of 546 Blalock-Taussig shunts performed in 478 patients. Cardiol Young 1998;8:486-90. https://doi.org/10.1017/s1047951100007150
9. Oofuvong M, Tanasansuttiporn J, Wasinwong W, et al. Predictors of death after receiving a modified Blalock-Taussig shunt in cyanotic heart children: a competing risk analysis. PLoS One 2021;16:e0245754. https://doi.org/10.1371/journal.pone.0245754
10. Song MH, Sato M, Ueda Y. Three-dimensional simulation of the Blalock-Taussig shunt using computational fluid dynamics. Surg Today 2001;31:688-94. https://doi.org/10.1007/s005950170071
11. Arnaz A, Piskin S, Oguz GN, Yalcinbas Y, Pekkan K, Sarıoglu T. Effect of modified Blalock-Taussig shunt anastomosis angle and pulmonary artery diameter on pulmonary flow. Anatol J Cardiol 2018;20:2-8. https://doi.org/10.14744/AnatolJCardiol.2018.54810
12. Liu J, Sun Q, Qian Y, Hong H, Liu J. Numerical simulation and hemodynamic analysis of the modified Blalock-Taussig shunt. Annu Int Conf IEEE Eng Med Biol Soc 2013;2013:707-10. https://doi.org/10.1109/EMBC.2013.6609598