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Revival of the modified Brock procedure: Midterm outcomes and clinical significance in cyanotic congenital heart disease

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ABSTRACT

Objectives: This study aimed to provide a detailed account of the midterm outcomes of the modified Brock procedure, a recently implemented procedure for patients with cyanotic congenital cardiac disease in our institution, with a particular focus on the clinical follow-up data.

Patients and methods: A total of 14 patients (7 males, 7 females; median age 4.5 years; range, 1 to 14.5 years) underwent the modified Brock procedure between January 2014 and January 2024. Relevant information was collected retrospectively, with a focus on the sizes of the pulmonary arteries.

Results: The preoperative median oxygen saturation and McGoon ratio were 71.5% (69.5 to 72.5%) and 1.35 (1.2 to 1.4), respectively. The postoperative course was uneventful. The median follow-up was seven years, and there was only one mortality two months after the operation. The complete repair was done in four patients during follow-up, with a median of 17.5 months after the initial procedure. The median McGoon ratio was 2 (1.9 to 2.125) in these patients. The postoperative median oxygen saturation was 93% (86.25 to 94.25%) and the median McGoon ratio was 1.6 (1.5 to 1.7) in patients awaiting complete repair surgery.

Conclusion: We concluded that the modified Brock procedure, when implemented with meticulous technique, is a viable choice in both short- and mid-term follow-up for palliative repair in patients with pulmonary artery anatomical constraints that preclude complete repair.

Keywords: Brock procedure, cyanotic, palliative surgery.

An additional source of pulmonary blood flow is required in symptomatic patients (severely cyanotic or spell) with ductus arteriosus-dependent cyanotic congenital heart diseases. All surgically created shunts require postoperative antiaggregant therapy and are associated with complications such as ongoing hypoxemia and the risk of occlusion. Furthermore, in some patients, the physiology of the shunt may be suboptimal, leading to diastolic runoff, which will eventually result in compromised coronary and visceral blood flow. Although it is well established that pulsatile pulmonary blood flow may result in enhanced pulmonary artery growth, shunts do not provide pulsatile blood flow in systole and diastole.[1]

Another palliative method described by Brock[2] involves a direct intervention on the stenotic pulmonary valve or infundibulum. Brock[3] was also the first to suggest that this procedure could also alleviate the pulmonary stenosis associated with tetralogy of Fallot (TOF).[2-5] The original technique has recently been revived with the use of modern cardiopulmonary bypass (CPB) techniques and surgical modifications. Studies showed that right ventricular outflow tract (RVOT)-directed palliative techniques appear to be safe and effective in achieving adequate pulmonary arterial growth until complete repair.[6-12]

In this study, we utilized a modified Brock procedure (patch enlargement of RVOT under CPB) as a palliative procedure of choice in patients with ductus-dependent cyanotic congenital heart diseases and hypoplastic pulmonary arterial bed. The study

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aimed to describe midterm results with the modified Brock procedure with emphasis on the clinical follow-up data.

PATIENTS AND METHODS

In the retrospective study, 14 patients underwent the modified Brock procedure as a palliative procedure between January 2014 and January 2024. Patients with discontinuous pulmonary arteries that required unifocalization procedures and patients with functionally univentricular heart physiology were not included in the study. Consent was obtained from the participants after providing them with all the necessary information, and the study was approved by the institutional review board. We reviewed demographic data, disease characteristics, preoperative echocardiographic, and other available imaging (catheterization and computed tomography [CT]) data, pulmonary artery Z-scores, McGoon indices, operational data, and postoperative parameters, such as vasoactive inotropic scores, time to extubation, length of stay in the critical care and hospital. Z-scores were primarily evaluated through angiographical measurements; however, if these data were unavailable, data from CT angiography or echocardiography were utilized. All patients completed follow-up. During follow-up, echocardiographic and other imaging data, details of corrective surgeries, and morbidity and mortality rates were determined. All surgical decisions were made by the joint multidisciplinary team on a case-by-case basis. The overarching principle was to ensure that the pulmonary arterial tree grew to its full potential for optimal repair. A written informed consent was obtained from each patient. The study protocol was approved by the Hacettepe University Health Sciences Research Ethics Committee (date: 24.05.2024, no: SBA 24/1013). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Surgical technique

Surgical technique was standard and performed by the same surgeon in all cases (pulmonary atresia with intact ventricular septum [PA-IVS] patient had membranous atresia). After median sternotomy, CPB was initiated with aortic and bicaval cannulation. Anatomy was observed considering the branch pulmonary arteries, the morphology of the aortic arch, and the coronary arterial trajectories. To eliminate competitive flow, patent ductus arteriosus or any additional pulmonary blood flow was always ligated when accessible. Having arrested the heart, a mini right ventriculotomy was performed on the infundibulum. Obstructing muscle bundles were divided and resected if necessary. It should be noted that excessive resection was not required, and only limited resection was done at this stage. The pulmonary valve was evaluated with Hegar dilators going from RVOT to pulmonary artery. The aim was to achieve approximately 75% of the normal size of the RVOT and pulmonary artery to prevent pulmonary flooding and right ventricular (RV) distension due to excessive pulmonary regurgitation. Thus, if the annulus was smaller, the main pulmonary artery was incised, and a commissurotomy was performed. A transannular incision was never made to prevent pulmonary regurgitation. However, serial dilatations were performed with incremental sizes of Hegar dilators. Bovine pericardium or Dacron velour sheet was used to augment incisions. We did not prefer the use of autologous pericardium to prevent RVOT aneurysmal dilatation. Moreover, the nondistensible RVOT patch facilitated the transmission of RV contraction energy to the distal pulmonary vascular bed, minimizing energy loss associated with distending a redundant RVOT patch. The patches were then sized to fit around a Hegar dilator that was 75% of the normal size. This step was crucial to avoid overburdening the right ventricle and causing disproportionate pulmonary blood. Consequently, appropriate pulmonary blood flow was provided, and RV function was maintained. Direct pressure measurements were consistently performed after the cessation of CPB, and a minimum pressure gradient of 40 mmHg was desired throughout RVOT with pulsatile pulmonary artery flow, oxygen saturation (SO_2) of 75 to 85%, and FiO_2 (fraction of inspired oxygen) of 30 to 50% to represent a balanced, banded ventricular septal defect (VSD). Before leaving the operating room, the patient was specifically observed for the requirement for inhaled nitric oxide, elevated FiO_2, or vasopressor administration to maintain SO_2 levels between 75 and 85%, which clearly indicates insufficient pulmonary blood flow.[6-10] In this scenario, further modifications to the patch were executed as required.

Statistical analysis

Statistical analyses were performed using Jamovi version 2.3.18.0. Continuous data were presented as median and interquartile range.

RESULTS

At the time of operation, the median age and median weight were 4.5 years (1 to 14.5 years) and 17.5 kg (7.75 to 51.25 kg), respectively. The median body surface area was 0.64 m^2 (0.4 to 1.5 m^2). Diagnoses were TOF with hypoplastic pulmonary arteries in 12 (86%) patients, pulmonary atresia with intact ventricular septum in one (7%), and TOF with absent left pulmonary artery in one (7%). The preoperative median oxygen saturation, hemoglobin, and hematocrit levels were 71.5% (69.5 to 72.5%), 17.1 g/dL (15.1 to 18.4 g/dL), and 53.6% (45.9 to 58.15 %), respectively. Table 1 summarizes the demographic

Table 1
Demographic and clinical characteristics of the patients

	n	%	Median	IQR
Demographics				
Age (years)			4.5	1-14.5
Sex				
Male	7	50		
Weight (kg)			17.5	7.75-51.25
BSA (m^2)			0.64	0.4-1.5
Preoperative variables				
Diagnoses				
TOF	12	86		
TOF-absent LPA	1	7		
PA-IVS	1	7		
SO_2 (%)			71	69-72
Hemoglobin (g/dL)			17.1	15.1-18.4
PA z-score (median, IQR)			–3	–3.95 - –2.75
McGoon index (median, IQR))			1.35	1.2-1.4
Intraoperative variables				
Bypass time (min)			85	60.5-109.5
Cross-clamp time (min)			39.5	26.25-52.75
Additional procedures				
Secundum ASD closure	2			
Pulmonary valve vegetectomy	1			
RVOT patch materials				
Dacron velour patch	7	50		
Bovine pericardial patch	7	50		
Postoperative variables				
MV time (h)			5	3-8
ICU stay (day)			4	4-5
In-hospital stay (day)			12	11.75-20.75
Vasoactive inotropic scores			15	5-25
SO_2 (%)			93	86.25-94.25
Hemoglobin (g/dL)			12.65	12.1-14.7
McGoon index (median, IQR)				
Patients had complete repair			2	1.9-2.125
Patients awaiting for complete repair			1.6	1.5-1.7

IQR: Interquartile range; BSA: Body survey area; TOF: Tetralogy of Fallot; LPA: Left pulmonary artery; PA: Pulmonary atresia; IVS: Intact ventricular septum; ASD: Atrial septal deffect; RVOT: Right ventricular outflow tract; MV: Mechanical ventilation; ICU: Intensive care unit.

Table 2
List of previous operations of the cohort

Previous procedures	n
Left mBTT shunt	5
Right mBTT shunt	4
Central shunt	3
Sano shunt	1
RVOT stent	2
Percutaneous balloon valvuloplasty	1

mBTT: modified Blalock-Taussig-Thomas shunt; RVOT: Right ventricular outflow tract.

and clinical characteristics of the patients. Fourteen patients underwent a total of 16 previous catheter or surgical interventions (1.14 interventions per patient). Of those 16 interventions, only three were catheter-directed RVOT stent implantations. The remaining 13 were different types of systemic-pulmonary artery shunt procedures. A detailed list of previous operations is shown in Table 2. The preoperative median Z-score of the pulmonary artery was –3 (–3.95 to –2.75), and the median McGoon ratio was 1.35 (1.2 to 1.4).

In terms of operative details, the median durations of CPB and aortic cross clamp were 85 min (60.5 to 109.5 min) and 39.5 min (26.25 to 52.75 min), respectively. Three patients underwent an additional cardiac operation at the time of the Brock procedure. Two were the closure of secundum atrial septal defect (ASD) (to decrease the risk of pulmonary overcirculation in the setting of large VSD and large ASD after the procedure) and the other was the vegetectomy of the infected foci in the pulmonary valve. In terms of patch material used during the Brock procedure, half of the patients had Dacron velour sheet, and the other half had bovine pericardial patch.

In all patients but one, the postoperative course was uncomplicated. All patients required inotropic support, with a median vasoactive inotropic score of 15. We were able to extubate all patients, except for one, in a median duration of 5 h (3 to 8 h), and the median length of stay in the intensive care unit was 4 days (4 to 5 days). The median duration of hospital stay was 12 days (11.75 to 27.25 days). There was one mortality that occurred two months after the operation. This patient had TOF with a hypoplastic pulmonary artery previously palliated with RVOT stent implantation, which was complicated and required emergency surgical operation. The patient collapsed in the 6th hour after the operation, and extracorporeal cardiopulmonary resuscitation was performed with central venoarterial extracorporeal membrane oxygenation (ECMO) cannulation. The patient was successfully weaned off ECMO on the fourth day of the circuit run but died two months after the initial operation due to extubation failure, tracheostomy requirement, and septic sequela.

Follow-up was complete for the remaining 13 patients with a median follow-up of seven years (6 to 8 years). Degree of pulmonary valvular regurgitation was mild-moderate in nine (70%) and moderate-severe in four (30%). Of these 13 patients, only four underwent complete repair during follow-up. The time interval between the modified Brock procedure and the complete repair was eight months, 11 months, two years, and three years. The growth of the pulmonary arterial tree as shown by the McGoon ratio in these patients was 1.2 to 1.9, 1.5 to 2.1, 1.4 to 1.9, and 1.2 to 2.2. The median McGoon ratio was 2 (1.9 to 2.125). Only one reoperation was required in four patients who underwent complete repair. It was a pulmonary valve replacement four years after total correction. For nine patients who had not undergone complete repair, only one reoperation for reaugmentation of the previously placed Brock patch was performed three years postoperatively. The postoperative median oxygen saturation, hemoglobin, and hematocrit levels were 93% (86.25 to 94.25%), 12.65 g/dL (12.1 to 14.7 g/dL), and 39.7% (37.6 to 44.7%), respectively. The postoperative median McGoon ratio was 1.6 (1.5 to 1.7). None of the patients had cyanotic spells, and there was no mortality during follow-up.

DISCUSSION

After the introduction of the Blalock-Thomas-Taussig (BTT) shunt in 1944, it garnered significant interest from both surgeons and the general public, becoming a widely adopted palliation method until it was eclipsed by direct corrective surgery. Later, Lord Russell Claude Brock innovated a closed transventricular pulmonary valvotomy technique, subsequently incorporating closed infundibular excision with a custom valvutome, which directly addresses outflow restriction and represents a genuine partial repair of the deformity.[2-4,13] The procedure was the first direct intracardiac intervention prior to the

development of echocardiography and CPB; however, this operation has not been widely adopted since then due to concerns about long-term survival, including recurrence of RVOT obstruction, arrhythmias, sudden cardiac mortality, and gradual biventricular dysfunction and failure, despite favorable short-term results, as indicated by reports.[6-12]

Right ventricular outflow tract stents, which have recently gained in popularity and are promoted as providing better hemodynamics and perhaps lower death rates compared to modified BTT (mBTT) shunts or ductal stenting, could be regarded as a transcatheter synthesis of a variant Brock procedure with an intracardiac Sano-type shunt, executed without CPB.[14-17] Therefore, surgical palliative procedures targeting RVOT have gained popularity recently. We employed the modified Brock procedure for patients with hypoplastic pulmonary arteries that hindered their ability to endure a full repair, as this technique offers advantages over BTT shunts. First, it facilitates antegrade flow via the natural pathway, promoting optimal uniform and symmetrical growth of the pulmonary arteries without distortion and gradually prepares the pulmonary bed for increased pulmonary blood flow. In extreme cases of TOF, it may facilitate the possibility of total correction. Second, the infundibulum and the RV cavity can also undergo further growth. Third, there may be a reduction in coronary steal attributed to decreased diastolic runoff. Fourth, the operation can also be repeated if necessary and facilitates further catheter interventions.[11,12,18] In our cohort, we managed to safely palliate patients with hypoplastic pulmonary arteries with a median SO_2 above 90% at midterm follow-up. Mortality was low (7%) with a straightforward postoperative course, and we were able to achieve complete repair in 30% of the patients during follow-up in a median of 17.5 months after the modified Brock procedure. Similarly, a retrospective study from Germany with 11 patients reported that there was no perioperative mortality, and 10 patients underwent elective complete repair.[8] They determined that palliative RVOT construction may offer the potential for complete repair in a severe form of TOF. The Paris group reported an early mortality rate of 2.7%, an interstage attrition rate of 6.6%, and successful biventricular repair in 84 (77%) patients with the use of a similar technique. They also reported that a Nakata index of 74 mm^2/m for the mBTT shunt and 102 mm^2/m for the right ventricle-to-pulmonary artery connection, indicating that the right ventricle-to-pulmonary artery connection appeared to facilitate superior pulmonary artery growth compared to the mBTT shunt.[9,10] Batlivala et al.[11] reported their experience of 17 patients who underwent modified RVOT procedure as palliation, and they concluded that it is a viable alternative that produces satisfactory results by preventing the possibility of sudden mortality associated with a shunt. Another study from China reported that the modified Brock procedure appears to be a more effective strategy that ensures safety and promotes satisfactory pulmonary arterial growth until complete repair compared to the mBTS procedure.[12]

On the other hand, disadvantages can be listed as the requirement of CPB and cardioplegia, and the challenging nature of the technique that requires precise division and resection (risk of pulmonary overflow).[18] If the valve is excessively opened, physiological issues may arise, particularly in the context of a large VSD, when a double outlet ventricle is present. In TOF, pulmonary stenosis prevents most left ventricular output from diverting to the low pressure pulmonary vascular system. The protective mechanism is abruptly removed when the valve is opened via the Brock technique. Subsequent extensive postoperative pulmonary mucosal edema, difficult tracheal extubation, and even heart failure are possible.[11,12,18,19] Therefore, it is crucial to open the pulmonary valve to an appropriate extent. Proper adjustment of the valve may produce sufficient pulmonary blood flow without significant blood shunting to the lungs. We did not encounter any of these problems as a result of our meticulous surgical technique, including restricted muscle resection, restricted RVOT enlargement, preservation of the annulus, and leaving a pressure gradient between the right ventricle and pulmonary artery. Furthermore, the fine-tuning of the RVOT patch size according to immediate hemodynamic parameters after weaning off CPB helped us prevent pulmonary overcirculation, which can result in sudden left ventricular dilation, bradycardia, and cardiac arrest. We strongly believe that all these preventive measures helped us achieve low mortality and straightforward postoperative recovery. Classically, it was often accepted that TOF management required total alleviation of obstruction in the RVOT. Recently, an emphasis has been placed on the preservation of the pulmonary valve and annulus, and a greater residual RVOT gradient

after surgery may be tolerated to prevent early and long-term complications.[19,20] Similar considerations are crucial when addressing RVOT for palliation, as frequently highlighted in previous articles.[6-12] As we managed to preserve the annulus in our cohort, we believe that pulmonary regurgitation would not be a significant problem after complete repair.

Although 30% of our cohort has undergone total repair, nine individuals were still awaiting full repair, with satisfactory growth of the pulmonary artery. Our institutional strategy for complete repair in patients with hypoplastic pulmonary arteries is to achieve a McGoon ratio of no less than 1.8. Consequently, although there was growth in pulmonary arteries, individuals awaiting complete repair still exhibited a McGoon ratio below 1.8. Their functional state and oxygen saturation levels were decent during the most recent follow-up. We employed a proactive approach during follow-up to assess pulmonary arterial growth. In terms of the reoperations following the modified Brock procedure, only one patient necessitated reaugmentation of the patch. Late reoperation for restrictive flow is typically not the result of an initial technical failure, as is widely recognized. It is often the result of the progressive relative stenosis of the initial procedure, which was caused by somatic growth, and the lack of development of the pulmonary artery to facilitate a full repair. Interestingly, few case reports have recently been published presenting long-term follow-up after the classical Brock procedure. One of the earliest patients who underwent the Brock procedure, a four-year-old child, was reported to have survived an additional 43 years without further surgical intervention.[21] Other patients have been reported to remain active and asymptomatic 43, 52, and even 63 years after the Brock procedure with good biventricular function.[22-24] Brock's[2] initial hypothesis that the pulmonary arteries would endure substantial development as a result of enhanced flow through the natural channel is also supported by these patients. This would suggest that a smaller number of patients would require total correction.[4,6,13]

This study was limited by the fact that it was conducted retrospectively and observationally at a tertiary referral center and with a small sample size over an extended period of time. The generalizability of our findings was also limited by the significant anatomical heterogeneity within the patient population. In addition, no comparison was made with other palliative procedures. Comprehensive statistical analysis was ultimately limited by the number of deaths, reoperations, and complications. It is imperative to collect additional data consistent with surgical techniques in a larger population of patients to derive association metrics.

In conclusion, we believe that palliative repair of RVOT with the modified Brock procedure appears to be a viable option and should be the primary palliative therapy, as opposed to conventional aortopulmonary shunts, for patients whose pulmonary artery anatomy prevents complete repair. The modified Brock procedure contributes to the preservation of RV function by maintaining an appropriate pressure gradient between the right ventricle and pulmonary artery, as well as enhancing pulmonary arterial growth through pulsatile flow. The potential drawback of pulmonary overcirculation was not a significant problem in our experience. Close follow-up of patients after palliative RVOT augmentation is essential.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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