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Staged surgical management of hypoplastic left heart syndrome: a single institution 12 year experience

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Objective: To describe a 12 year experience with staged surgical management of the hypoplastic left heart syndrome (HLHS) and to identify the factors that influenced outcome.
Methods: Between December 1992 and June 2004, 333 patients with HLHS underwent a Norwood procedure (median age 4 days, range 0–217 days). Subsequently 203 patients underwent a bidirectional Glenn procedure (stage II) and 81 patients underwent a modified Fontan procedure (stage III). Follow up was complete (median interval 3.7 years, range 32 days to 11.3 years).
Results: Early mortality after the Norwood procedure was 29% (n = 95); this decreased from 46% (first year) to 16% (last year; $p < 0.05$). Between stages, 49 patients died, 27 before stage II and 22 between stages II and III. There were one early and three late deaths after stage III. Actuarial survival (SEM) was 58% (3%) at one year and 50% (3%) at five and 10 years. On multivariable analysis, five factors influenced early mortality after the Norwood procedure ($p < 0.05$). Pulmonary blood flow supplied by a right ventricle to pulmonary artery (RV-PA) conduit, arch reconstruction with pulmonary homograft patch, and increased operative weight improved early mortality. Increased periods of cardiopulmonary bypass and deep hypothermic circulatory arrest increased early mortality. Similar factors also influenced actuarial survival after the Norwood procedure.
Conclusion: This study identified an improvement in outcome after staged surgical management of HLHS, which was primarily attributable to changes in surgical technique. The RV-PA conduit, in particular, was associated with a notable and independent improvement in early and actuarial survival.

Hypoplastic left heart syndrome (HLHS) refers to the group of congenital cardiac abnormalities characterised by severe stenosis or atresia of the mitral and aortic valves, diminutive ascending aorta, and left ventricular hypoplasia.[1] The left ventricle is unable to support the systemic circulation, which is maintained by the right ventricle through a patent ductus arteriosus. HLHS accounts for 2.5% of congenital heart defects but is responsible for up to 25% of all deaths within the first week of life.[2] Without surgical palliation, 95% of children die within the first month of life.[3]

In 1983, Norwood *et al*[4] reported the first successful surgical palliation of HLHS, which consisted of a Norwood procedure followed by the Fontan procedure. In 1990, Bridges *et al*[5] described the bidirectional cavopulmonary anastomosis as an intermediate staging operation for the management of high risk candidates for the Fontan procedure, such as patients with HLHS. This three stage surgical palliation remains the most common treatment for patients with HLHS.

Outcome after surgical palliation for HLHS has been improved substantially. This has been attributed to modifications in surgical technique and perioperative medical care, together with a better understanding of postoperative physiology.[6] One of the most important recent developments has been the right ventricle to pulmonary artery (RV-PA) conduit as an alternative source of pulmonary blood flow to the right modified Blalock-Taussig shunt (RMBTS).[7] The RV-PA conduit is reportedly associated with more stable postoperative haemodynamic function,[8–10] superior ventricular function,[11] and improved early survival.[10] The early survival after the Norwood procedure in contemporary series varies between 73–80%,[12–14] although an increasing number of centres have reported hospital survival rates greater than 90%.[10 15 16]

Early outcome after the subsequent stages of surgical palliation have also improved progressively.[17] The introduction of the bidirectional cavopulmonary anastomosis as an interim staging procedure has improved survival after the modified Fontan procedure. Early mortality after the Fontan procedure ranges between 2–7%[18 19] and does not appear to be influenced by the morphology of the single, functional ventricle.[19]

Information describing the medium and long term outcome of surgical palliation for patients with HLHS is limited.[12 14 20 21] This study was undertaken to describe our 12 year single institution experience with the surgical palliation of HLHS. We sought to identify those anatomical and technical factors that influenced outcome after the modified Norwood procedure.

METHODS

Between December 1992 and June 2004, 366 consecutive patients underwent a modified Norwood procedure at the Diana Princess of Wales Children's Hospital, Birmingham, UK. Three hundred and thirty three patients had HLHS. Thirty three patients with functional single ventricle anatomy

Abbreviations: BDG, bidirectional Glenn; CI, confidence interval; EWMA, exponentially weighted moving average; HLHS, hypoplastic left heart syndrome; LR, likelihood ratio; OR, odds ratio; PTFE, polytetrafluoroethylene; RV-PA, right ventricle to pulmonary artery; RMBTS, right modified Blalock-Taussig shunt

of left ventricular morphology underwent a modified Norwood procedure and were not enrolled in this study.

Patient population

The diagnosis of HLHS was based on detailed two dimensional echocardiography. Most patients had classic HLHS (n = 290, 87%). The remaining 43 patients had an HLHS variant (table 1) characterised by left ventricular hypoplasia and systemic outflow tract obstruction. There were 219 male (66%) and 114 female patients.

The median diameter of the ascending aorta was 3.0 mm (range 1.0–10.0 mm) and was ⩽ 2.0 mm in 82 patients (25%). The majority of patients had evidence of a discrete coarctation ridge (n = 252, 75%). Fifty four patients (16.2%) had additional cardiac abnormalities (table 1). Fourteen patients (4.2%) were born prematurely (gestational age ⩽ 36 weeks) and 18 patients (5.4%) had diagnosed extracardiac abnormalities, including major structural or genetic abnormalities (table 1).

Most patients were initially stabilised with medical management. Seven patients (2.1%) had a surgical procedure (atrial septectomy, n = 4; coarctation repair, n = 2; open aortic valvotomy, n = 2) and four patients (1.2%) had balloon atrial septostomy before the Norwood procedure.

Norwood procedure

The Norwood procedure was performed at a median age of 4 days (range 0–217 days). Most (n = 265, 80%) were operated on within the first seven days and only 13 (3.9%) were operated on at > 30 days of age. The median weight at operation was 3.1 kg (range 1.7–6.6 kg) and 48 patients (14%) weighed ⩽ 2.5 kg.

Table 1 Cardiac anatomy

Primary cardiac anatomy	
Classic hypoplastic left heart syndrome	290 (87%)
Variants of hypoplastic left heart syndrome	43 (13%)
Unbalanced atrioventricular septal defect	16
Double outlet right ventricle with mitral atresia	15
Critical aortic stenosis with hypoplastic left ventricle	6
Double inlet, double outlet right ventricle	3
Mitral atresia with aortic arch hypoplasia	3
Additional cardiac abnormalities	
Arch abnormalities	16 (4.8%)
Interrupted aortic arch (type A)	1
Interrupted aortic arch (type B)	2
Interrupted aortic arch (type C)	2
Right subclavian artery arising from descending thoracic aorta	11
Abnormal systemic venous drainage	31 (9.3%)
Bilateral superior venae cavae	28
Azygos or hemiazygos continuation of inferior vena cava	2
Left atrial isomerism	5
Abnormal pulmonary venous drainage	5 (1.5%)
Total anomalous pulmonary venous drainage	2
Partial anomalous pulmonary venous drainage	2
Pulmonary venous obstruction	1
Congenital heart block	2 (0.6%)
Associated genetic anomalies and major structural abnormalities	
Genetic anomalies	7 (2.1%)
Turner's syndrome	2
DiGeorge's syndrome	1
Other chromosomal microdeletion	4
Major structural abnormalities	14 (4.2%)
Congenital hydrocephalus	2
Microcephaly	1
Agenesis of corpus callosum	1
Cerebral palsy	1
Congenital hypothyroidism	2
Tracheo-oesophageal fistula	2
Congenital bronchomalacia	1
Bilateral renal dysplasia	1
Choanal atresia	1
Perinatal (preoperative) necrotising enterocolitis	3

One of three surgeons performed all operations with the use of deep hypothermic cardiopulmonary bypass with periods of circulatory arrest for arch reconstruction. Antegrade cerebral perfusion, introduced in September 2002, was used during arch reconstruction for patients whose head and neck vessels were able to accommodate an arterial cannula. Myocardial protection was provided with a single dose of cold crystalloid cardioplegia (30 ml/kg) administered before circulatory arrest. The median durations of cardiopulmonary bypass, aortic cross clamp, and deep hypothermic circulatory arrest were 71 minutes (range 17–323 minutes), 51 minutes (range 0–109 minutes), and 55 minutes (range 0–121 minutes), respectively.

The main pulmonary artery was divided at the level of the bifurcation and the distal pulmonary arteries were repaired with direct suture (n = 97, 29%) or a patch (n = 236, 71%). An atrial septectomy was performed during circulatory arrest, usually through the venous cannulation site. The arch was reconstructed with one of two established techniques: the original technique consisted of arch reconstruction without the use of additional patch material (n = 129, 39%)[22 23]; the second technique, used exclusively since April 1999, consisted of arch reconstruction with a pulmonary homograft patch (n = 204, 61%).[24]

Pulmonary blood flow was established with an RMBTS (n = 258, 77%) or RV-PA conduit (n = 73, 22%). Two patients (0.6%) with an anomalous right subclavian artery arising from the descending thoracic aorta had a 3 mm shunt between either the proximal main pulmonary artery or the aortic arch and the right pulmonary artery. The RMBTS was formed by anastomosing a polytetrafluoroethylene (PTFE) tube conduit (Gore-tex, WL Gore & Associates (UK) Ltd, Livingston, UK) between the innominate artery and the upper border of the right pulmonary artery. The median size of this shunt was 3.5 mm (range 3–5 mm) and the mean (SD) shunt size indexed to body weight was 1.07 (0.18) mm/kg. The RV-PA conduit was introduced in March 2002 and consisted of a PTFE tube conduit that passed to the left of the neoaorta (n = 17).[7 24] More recently, this technique was modified so that the conduit passed to the right of the neoaorta (n = 56). The median size of the RV-PA conduit was 5 mm (range 4–5 mm) and mean (SD) indexed shunt size was 1.65 (0.30) mm/kg.

Sternal closure was delayed in virtually all patients. Inotropic support usually comprised dobutamine (10 μg/kg/min) or milrinone (0.3–0.7 μg/kg/min) plus adrenaline (0–0.3 μg/kg/min) as required. Mechanical ventilation with pressure regulated neonatal ventilators was adjusted to maintain arterial oxygen saturations of 70–80% and arterial carbon dioxide tension between 35–45 mm Hg. Inspired carbon dioxide and nitrogen were not used to manipulate the pulmonary vascular resistance. Patients were discharged from hospital on a prescription of aspirin (5 mg/kg/day) and an oral diuretic. Patients with impaired right ventricular function or clinically important systemic atrioventricular valvar regurgitation also received an angiotensin converting enzyme inhibitor (captopril).

Stage II and stage III procedures

Cardiovascular function was assessed by echocardiography and elective cardiac catheterisation before the bidirectional Glenn procedure (BDG; stage II) and modified Fontan procedure (stage III). Thirty seven patients required cardiological intervention before stage II, primarily for neoaortic arch obstruction (n = 34).[25] Thirty six patients also required cardiological intervention before stage III. Most (n = 27) had

balloon dilatation of the pulmonary arteries with or without stent insertion. Twelve patients had balloon dilatation of residual (n = 5) or previously untreated (n = 7) neoaortic arch obstruction.

Two hundred and three patients underwent a BDG at a median age of 4.9 months (range 27 days to 22.8 months) and median interval of 4.7 months (range 18 days to 22.6 months) after the Norwood procedure. Concomitant surgical procedures performed in 84 patients (41%) were pulmonary artery patch augmentation (n = 76), patch augmentation of the neoaortic arch (n = 7), atrioventricular valve annuloplasty (n = 4), atrial septectomy (n = 1), and insertion of a permanent pacemaker (n = 1).

Eighty one patients underwent the modified Fontan procedure at a median age of 4.4 years (range 2.2–6.6 years) and median interval of 4.0 years (range 1.9–6.1 years) after stage II. The modified Fontan procedure was performed with a lateral atrial tunnel (n = 7, 8.6%) or an extracardiac conduit (n = 74, 91.4%) and was fenestrated in 57 patients (70%).[19] Concomitant surgical procedures performed in 27 patients (33%) were pulmonary artery patch augmentation (n = 24), atrioventricular valve annuloplasty (n = 1), surgical occlusion of the native aortic valve (n = 1), and insertion of a permanent pacemaker (n = 1). All patients received postoperative warfarin, with a target international normalised ratio of 2.0–3.0.[19]

Data analysis

For this retrospective study we reviewed hospital records, operation notes, and cardiac catheterisation data. All patients have been followed up since discharge by a paediatric cardiologist. Follow up was complete with a median interval of 3.7 years (range 32 days to 11.3 years).

Data were examined by analysis of variance with SPSS for Windows (version 12, SPSS Inc, Chicago, Illinois, USA). Continuous variables are expressed as mean (SD) or median (range) and comparative univariable analyses were made with the *t* test, Mann-Whitney U test, or Wilcoxon signed rank test. Binomial or ordinal data are expressed as percentages and comparative univariable analyses were made with the χ^2 test, two sided Fisher's exact test, or binomial logistic regression. A probability value of $p < 0.05$ was indicated a significant difference between groups.

Early mortality (inpatient or 30 day) was estimated by a running estimate, in which equal weight was apportioned to each case, or an exponentially weighted moving average (EWMA), in which previous observations were systematically down weighted by 5% for each case.[26] With this EWMA, the experience with the 14th previous patient carried about half the weight of the last patient seen. The 95% confidence intervals (CIs) for each estimate were calculated.[27]

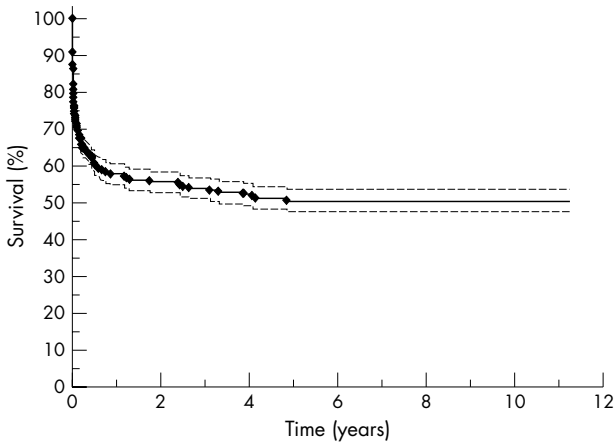

Figure 1 Actuarial survival after staged surgical management of the hypoplastic left heart syndrome. Data are mean (SD).

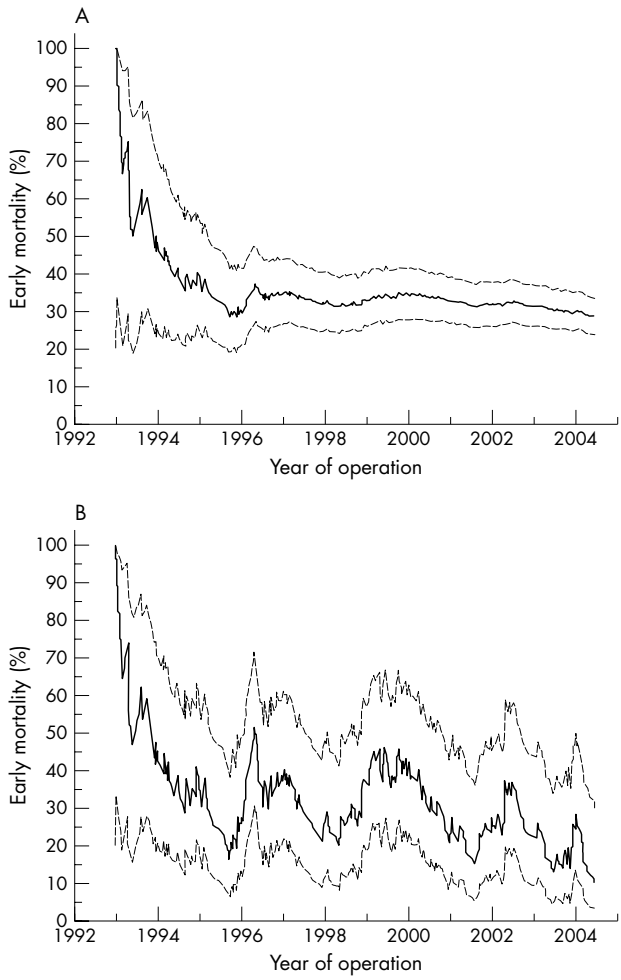

Figure 2 Serial estimates of early mortality with 95% confidence interval. (A) Running estimate. (B) Exponentially weighted moving average with 5% down weighting for each case.

Early mortality and actuarial survival after the Norwood procedure, BDG, and modified Fontan procedure were evaluated with a series of morphological, preoperative, and operative variables by univariable and multivariable analyses. Univariable analyses of early outcome measures were made with the χ^2 test, two sided Fisher's exact test, and binomial logistic regression. Variables with a value of $p \leqslant 0.1$ were included in a stepwise logistic regression model. Results of these analyses are expressed as odds ratios (ORs) with 95% CIs for variables with a value of $p < 0.05$. Actuarial survival was estimated with the Kaplan-Meier product limit method. These results are expressed as probability estimates (SEM). Univariable analyses of actuarial outcome measures were made with the log rank test. Variables with a value of $p \leqslant 0.1$ were included in a stepwise Cox regression analysis. Results of these analyses are expressed as likelihood ratios (LRs) with 95% CIs for variables with a value of $p < 0.05$.

RESULTS

At the time of follow up, 183 patients survived (55%) and 150 had died (45%). Two patients had undergone orthotopic heart transplantation (0.6%). The actuarial survival (SEM) was 58% (3%) at one year, 54% (3%) at three years, and 50% (3%) at five and 10 years (fig 1).

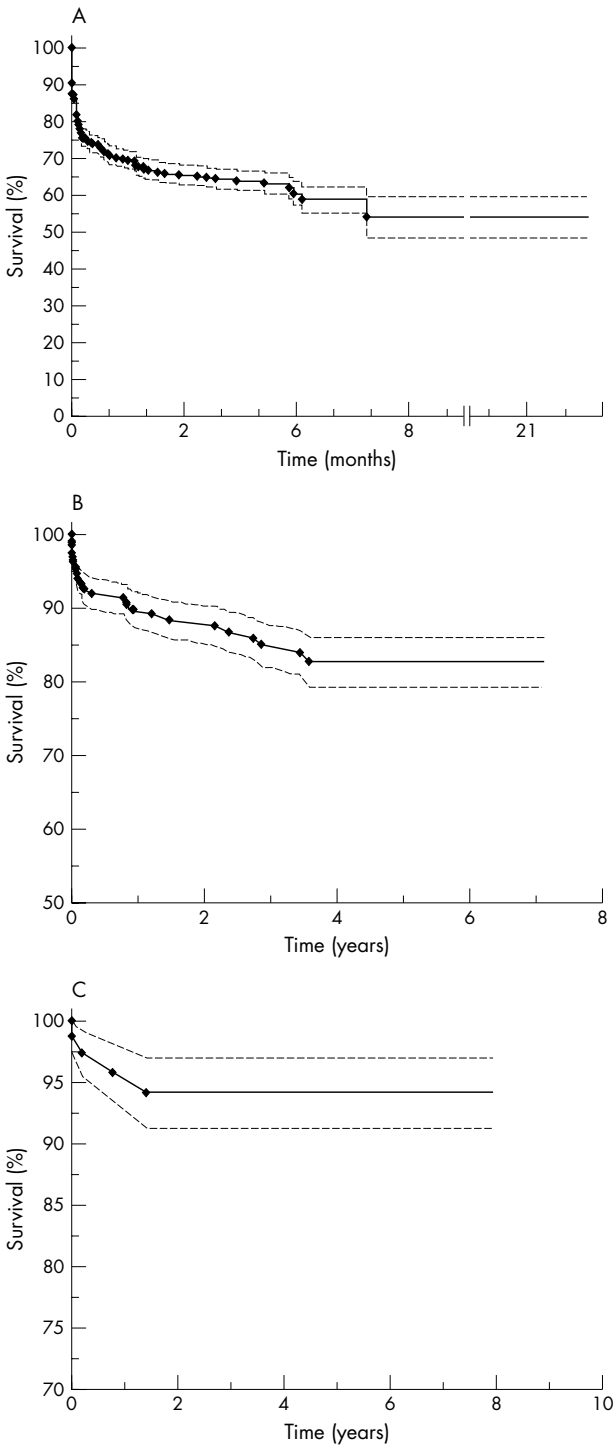

Figure 3 Actuarial survival after the three stages of surgical management: (A) with Norwood circulation; (B) with bidirectional Glenn procedure; (C) with Fontan circulation.

Early mortality and actuarial survival with a Norwood circulation

Early mortality after the Norwood procedure was 29% (n = 95). Figure 2 illustrates the estimates of early mortality over the study period. Between December 1992 and December 1995, the running estimate declined from 100% (95% CI 21% to 100%) to 30% (95% CI 20% to 41%). The running estimate remained relatively constant thereafter, and was 29% (95% CI 24% to 34%) in June 2004 (fig 2A). The EWMA showed a similar trend; the estimated early mortality declined from 100% (95% CI 21% to 100%) in December 1992 to 17% (95% CI 6% to 38%) in September 1995. The EWMA also identified continued improvement in early outcome, such that estimated early mortality was 10% (95% CI 3% to 30%) in June 2004 (fig 2B).

Twenty seven patients died between stage I and stage II, at a median interval of 70 days after the Norwood procedure (range 31 days to eight months). Actuarial interstage mortality (SEM) was 7.9% (1.8%) at three months and 15% (3%) at six months. Overall actuarial survival (SEM) with a Norwood circulation was 66% (3%) at three months and 61% (3%) at six months after the Norwood procedure (fig 3A).

Multivariable analysis identified five factors that were independently associated with early mortality after the Norwood procedure (table 2). An RV-PA conduit (OR 0.2, 95% CI 0.1 to 0.5) and increased weight at operation (OR 0.8 for each 250 g increase, 95% CI 0.7 to 0.9) reduced the risk of early mortality. Arch reconstruction without the use of additional material (OR 2.0, 95% CI 1.1 to 3.8), increased duration of cardiopulmonary bypass (OR 1.6 for each 15 minute increase, 95% CI 1.3 to 1.9), and increased duration of deep hypothermic circulatory arrest (OR 1.4 for each 15 minute increase, 95% CI 1.1 to 1.8) increased the risk of early mortality.

Multivariable analysis identified five factors that were independently associated with actuarial survival after the Norwood procedure (table 3). An RV-PA conduit (LR 0.3, 95% CI 0.2 to 0.6) and an increased weight at operation (LR 0.9 for each 250 g increase, 95% CI 0.8 to 0.9) reduced the risk of mortality. Female sex (LR 1.7, 1.2 to 2.4), increasingly prolonged cardiopulmonary bypass (LR 1.4 for each 15 minutes increase, 95% CI 1.2 to 1.5), and increasingly prolonged deep hypothermic circulatory arrest (LR 1.3 for each 15 minute increase, 95% CI 1.1 to 1.5) increased the risk.

On univariable analysis, female sex was the only factor that adversely influenced actuarial interstage survival after the Norwood procedure (LR 3.5, 95% CI 1.7 to 7.0, $p < 0.001$).

Early mortality and actuarial survival after stages II and III

Early mortality after stage II was 3.9% (n = 8). Between May 1993 and October 1996, the running estimate of early mortality increased from 0% (95% CI 0% to 79%) to 10% (95% CI 5% to 22%). It subsequently declined to 4% (95% CI 2% to 8%) at the end of the study (fig 4). There were 13 late deaths before stage III at a median interval of 18 months after the BDG (range 51 days to 3.6 years). Four patients (2.0%) required takedown of the BDG and restoration of the Norwood circulation; all subsequently died. Two patients underwent orthotopic heart transplantation 2.2 and 2.9 years after stage II. The actuarial survival (SEM) with a BDG was 90% (2%) at one year, 85% (3%) at three years, and 83% (3%) at five years after stage II (fig 3B).

Univariable analysis identified a progressive improvement in early mortality over the study period ($p < 0.01$). No factors were associated with survival after stage II on univariable analysis.

One patient died early after stage III and another patient required acute takedown of the Fontan circulation and reformation of the BDG. Three patients died late at 69 days, 9.4 months, and 1.4 years after stage III. The actuarial survival (SEM) with a Fontan circulation was 96% (2%) at one year and 94% (3%) at three, five, and seven years after stage III (fig 3C). Univariable analysis did not identify any factors independently associated with survival after stage III.

Table 2 Logistic regression analyses for early mortality after a Norwood procedure

	Early mortality	
Risk factor	Univariable p value	Multivariable OR (95% CI)
Size of ascending aorta (per mm increase)	0.02	NA
Preoperative ventricular function	<0.05	NA
Height at operation (per quartile increase)	0.005	NA
Weight at operation (per 250 g increase)	0.001	0.8 (0.7 to 0.9; p<0.001)
Body surface area at operation (per dm^2 increase)	0.001	NA
Pulmonary blood flow (RV-PA conduit *v* RMBTS)	0.01	0.2 (0.1 to 0.5; p=0.001)
Arch reconstruction (no additional material *v* patch augmentation)	0.08	2.0 (1.1–3.8; p=0.02)
Surgeon	<0.05	NA
Year of operation	0.01	NA
Duration of CPB (per 15 minute increase)	0.03	1.6 (1.3–1.9; p<0.001)
Duration of DHCA (per 15 minute increase)	<0.001	1.4 (1.1–1.8; p<0.05)
Duration of cardiopulmonary support (per 15 minute increase)	0.001	NA

CI, confidence interval; CPB, cardiopulmonary bypass; DHCA, deep hypothermic circulatory arrest; NA, not applicable; OR, odds ratio; RMBTS, right modified Blalock-Taussig shunt; RV-PA, right ventricle to pulmonary artery.

DISCUSSION

The management of HLHS continues to present one of the greatest challenges in congenital heart surgery. The optimal surgical management for these patients remains controversial. Alternative strategies, such as neonatal orthotopic heart transplantation, have been advocated. However, staged surgical palliation has gained acceptance as the primary treatment option for these patients.[6] Nevertheless, the Norwood procedure for HLHS is associated with an operative mortality that is substantially higher than that associated with other congenital cardiac defects requiring neonatal repair.[28] Furthermore, the long term outcome after staged surgical palliation has not been clearly defined.

This study has reported a series of 333 patients after staged surgical palliation for HLHS. This represents our entire, unselected experience with the surgical management of HLHS since its inception in December 1992. Five and 10 year survival after the Norwood procedure were 50%. These figures are consistent with previous reports in which the five year survival ranged between 40–59%.[12 14 21]

We observed a notable improvement in outcome after the Norwood procedure over the study period. Many authors have reported a similar improvement in outcome over time.[12 13 21] Several reasons have been postulated to explain this ''era effect'', including increasing antenatal diagnosis, improved perioperative medical management, and modifications in surgical technique.[12 13] In our experience, the improvements in early mortality were primarily attributable to modifications in surgical technique. Aortic arch reconstruction with a pulmonary homograft patch and, more recently, the use of an RV-PA conduit were independently associated with an improvement in early mortality.

Reconstruction of the aortic arch is central to the Norwood procedure. It relieves the systemic outflow tract obstruction and establishes unobstructed systemic and coronary blood flow from the right ventricle. In 1986, Jonas *et al*[29] described a modified Norwood procedure, in which the aortic arch was reconstructed with a pulmonary homograft patch. The patch extended from the ascending aorta at the level at which the main pulmonary artery was transected, throughout the arch concavity, and into the descending thoracic aorta distal to the duct insertion. This technique has been adopted as the standard method of arch reconstruction for HLHS.[30]

In 1995, we described an alternative technique for arch reconstruction that did not use any patch material.[22] By using only native tissue, this technique avoided potential risks associated with a pulmonary homograft patch, such as failure of normal arch development, patch degeneration, and the risk of rupture or false aneurysm formation after balloon dilatation of any residual coarctation. In a subsequent series of 120 neonates with HLHS,[23] we reported that arch reconstruction without additional material was possible in 85% of cases. However, in the remaining 15%, arch reconstruction was supplemented with a pulmonary homograft patch to avoid excessive tension on the arch or its branch arteries or to prevent arch distortion. Furthermore, this technique did not address the problem of a diminutive ascending aorta.

Table 3 Logistic regression analyses for actuarial survival with Norwood circulation

	Actuarial survival	
Risk factor	Univariable p value	Multivariable LR (95% CI)
Sex (female *v* male)	<0.01	1.7 (1.2 to 2.4; p<0.01)
Size of main pulmonary artery	0.05	NA
Height at operation (per quartile increase)	<0.05	NA
Weight at operation (per 250 g increase)	<0.01	0.9 (0.8 to 0.9; p=0.001)
Body surface area at operation (per dm^2 increase)	<0.005	NA
Pulmonary blood flow (RV-PA conduit *v* RMBTS)	<0.05	0.3 (0.2 to 0.6; p<0.001)
Surgeon	<0.05	NA
Year of operation	<0.005	NA
Duration CPB (per 15 minute increase)	<0.001	1.4 (1.2 to 1.5; p<0.001)
Duration DHCA (per 15 minute increase)	<0.001	1.3 (1.1 to 1.5; p<0.05)
Duration of cardiopulmonary support (per 15 minute increase)	<0.001	NA

LR, likelihood ratio.

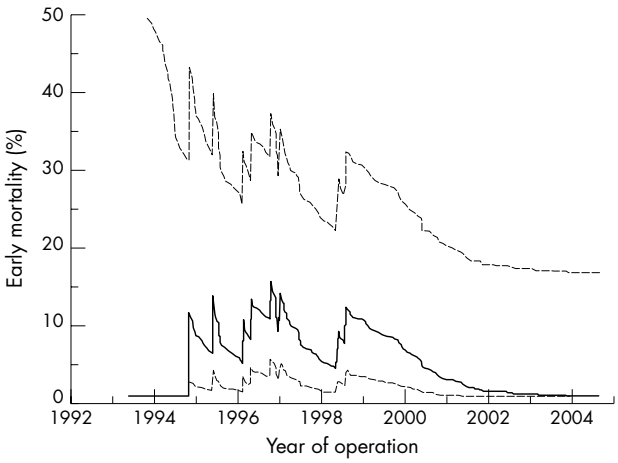

Figure 4 Running estimate of early mortality with 95% confidence intervals.

We have since adopted a more reproducible method of arch reconstruction with a pulmonary homograft patch, which could be applied to all patients irrespective of arch morphology.[24] This technique preserves the continuity of the aortic arch and may prevent arch distortion. In addition, it has enabled more aggressive augmentation of the ascending aorta. The pulmonary homograft patch is extended proximally into the aortic root and below the level of the transected end of the main pulmonary artery, as reported by Jonas *et al*.[29] Consequently, this technique may improve coronary perfusion in patients who are otherwise at risk of myocardial ischaemia.[31] In the present study, multivariable analysis showed that arch reconstruction with a pulmonary homograft patch reduced early mortality by half. A similar advantage was not apparent when actuarial survival was analysed.

During the Norwood procedure, pulmonary blood flow is usually established with an RMBTS,[30] although central shunts have also been described.[29 32] Increasing experience with the Norwood procedure has resulted in the use of smaller shunts, which optimise the systemic to pulmonary blood flow ratio at $\leqslant 1$, thereby preventing excessive pulmonary blood flow.[33] In general, we used a 3.5 mm shunt in patients who weighed $\geqslant 2.5$ kg and a 3 mm shunt in patients who weighed < 2.5 kg. Nevertheless, maldistribution of the cardiac output was implicated as a major cause of early death in our own experience.[23]

The RV-PA conduit was initially described as the source of pulmonary blood flow by Norwood *et al*[32] and subsequently developed by Kishimoto *et al*[34] and Sano *et al*.[7] The principle advantage of the RV-PA conduit is that it abolishes the diastolic runoff from the systemic to the pulmonary circulation, which characterises the RMBTS. This raises diastolic pressure and increases coronary perfusion pressure.[7] Abolishing diastolic runoff may also ensure a more stable balance between the systemic and pulmonary circulations, such that systemic and coronary blood flows are less influenced by fluctuations in pulmonary vascular resistance.[8]

Some authors have reported improved early postoperative haemodynamic function associated with the RV-PA conduit compared with the RMBTS.[7 8 10] Hughes *et al*[11] reported the RV-PA conduit was associated with better early postoperative right ventricular function. Pizarro *et al*[10 35] also suggested that the RV-PA conduit may have a beneficial impact on early and midterm outcome after the Norwood procedure. In the present study, multivariable analysis showed that the modified Norwood procedure with an RV-PA conduit was associated with a substantial improvement in early mortality and actuarial survival.

Several other factors have been identified as risk factors for mortality after the Norwood procedure, including prematurity[12 13 20]; anatomical subtype[20 23 36]; additional cardiac defects, associated extracardiac defects, or chromosomal abnormalities[14]; and lower weight at operation.[21] In the present study, lower weight at operation was identified as an independent risk factor for early mortality and actuarial survival after the Norwood procedure. This finding is consistent with previous reports.[12 13] Nevertheless, the outlook for these patients appears to have improved somewhat and the introduction of the RV-PA conduit may further improve the outcome for these high risk patients.[7 13]

This study also identified longer cardiopulmonary bypass and deep hypothermic circulatory arrest times as independent risk factors for early mortality and actuarial survival after the Norwood procedure, in keeping with previous reports.[13 37] This probably reflects the increased risk associated with longer and more complex procedures. We also identified female sex as an independent risk factor for actuarial survival, although the importance of this finding is unclear.

Despite improvements in early outcome after the Norwood procedure, there is a continued attrition before stage II. In the current study, the actuarial interstage mortality was 15% at six months after the Norwood procedure. This is consistent with previous reports in which interstage mortality ranged between 9–16%.[6 12 13 15] The cause of interstage death has not been fully elucidated and a substantial proportion of deaths remain sudden and unexpected.[38] Nevertheless, Ghanayem *et al*[39] reported complete interstage survival after the introduction of a home surveillance programme that enabled at risk patients to be identified and treated aggressively.

Early outcome after subsequent stages of surgical palliation has improved over time.[17] The introduction of the superior cavopulmonary anastomosis as an intermediate operation (stage II) has been associated with improved overall survival for patients with HLHS.[17] This study has identified that the BDG is associated with a low operative mortality in this high risk population. Nevertheless, we identified a continued attrition of patients between stage II and stage III. The actuarial interstage mortality was 9% at three years after stage II, which is higher than previously reported.[17 40] The reason for this increased risk is not clear but may be a consequence of differences in the timing of stage III. Most North American units complete the Fontan circulation by 2 years of age. In contrast, we perform the modified Fontan procedure when patients develop progressive cyanosis or exertional dyspnoea, which is generally when they are 4–5 years of age.[19] There are no data to confirm the optimal timing for stage III.

Early mortality after the modified Fontan procedure in the current era ranges between 2–7%.[18 19] This study has shown that comparable results can be achieved in patients with HLHS. This group has traditionally been regarded as being at high risk for the Fontan procedure, primarily because the morphological right ventricle must support the Fontan circulation.[18] However, this study corroborates more recent reports of equivalent survival after the modified Fontan procedure in patients with a single functional ventricle of left or right ventricular morphology.[19]

Study limitations

The retrospective design of this study precluded the assessment of risk factors not entered in the model. Complete data on known risk factors for mortality, such as antenatal diagnosis and primary cardiac anatomy, were not available for many patients and were not included in the analysis. We

also identified a high level of correlation between some of the variables, which may have confounded the multivariable analysis and prevented us from identifying independent associations between variables and the outcome measures. Finally, the duration of follow up is limited.

Conclusion

This study has analysed the 12 year survival for patients undergoing staged palliation for HLHS. This study has shown a notable improvement in survival for these patients, which was primarily attributable to changes in surgical technique. The introduction of the RV-PA conduit to supply pulmonary blood flow, in particular, was associated with a major improvement in survival after the Norwood procedure. It remains to be seen whether these encouraging results are reflected in improved longer term outcome for these patients.

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