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Relationship of Surgical Approach to Neurodevelopmental Outcomes in Hypoplastic Left Heart Syndrome

William T. Mahle, MD[a], Karen J. Visconti, PhD[b], M. Catherin Freier, PhD[c], Stephen M. Kanne, PhD[d], William G. Hamilton, PhD[a], Angela M. Sharkey, MD[d], Richard E. Chinnock, MD[c], Kathy J. Jenkins, MD[b], Peter K. Isquith, PhD[e], Thomas G. Burns, PsyD[a], Pamela C. Jenkins, MD, PhD[e]

[a]Children's Healthcare of Atlanta, Atlanta, Georgia; [b]Children's Hospital, Boston, Massachusetts; [c]Loma Linda University Children's Hospital, Loma Linda, California; [d]St Louis Children's Hospital, St Louis, Missouri; [e]Dartmouth Medical School, Hanover, New Hampshire

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ABSTRACT

OBJECTIVE. Two strategies for surgical management are used for infants with hypoplastic left heart syndrome (HLHS), primary heart transplantation and the Norwood procedure. We sought to determine how these 2 surgical approaches influence neurodevelopmental outcomes at school age.

METHODS. A multicenter, cross-sectional study of neurodevelopmental outcomes among school-aged children (>8 years of age) with HLHS was undertaken between July 2003 and September 2004. Four centers enrolled 48 subjects, of whom 47 completed neuropsychologic testing. Twenty-six subjects (55%) had undergone the Norwood procedure and 21 (45%) had undergone transplantation, with an intention-to-treat analysis. The mean age at testing was 12.4 ± 2.5 years. Evaluations included the Wechsler Abbreviated Scale of Intelligence, Clinical Evaluation of Language Fundamentals, Wechsler Individual Achievement Test, and Beery-Buktenica Developmental Test of Visual-Motor Integration.

RESULTS. The mean neurocognitive test results were significantly below population normative values. The mean full-scale IQ for the entire cohort was 86 ± 14. In a multivariate model, there was no association of surgical strategy with any measure of developmental outcome. A longer hospital stay, however, was associated significantly with lower verbal, performance, and full-scale IQ scores. Aortic valve atresia was associated with lower math achievement test scores.

CONCLUSIONS. Neurodevelopmental deficits are prevalent among school-aged children with HLHS, regardless of surgical approach. Complications that result in prolonged hospitalization at the time of the initial operation are associated with neurodevelopmental status at school age.

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Key Words
hypoplastic left heart syndrome, neurodevelopmental outcome, transplantation, Norwood procedure

Abbreviations
BASC—Behavior Assessment System for Children
BRIEF—Behavior Rating Inventory of Executive Function
CELF—Clinical Evaluation of Language Fundamentals
DHCA—deep hypothermic circulatory arrest
HLHS—hypoplastic left heart syndrome
VMI—Visual-Motor Integration
WASI—Wechsler Abbreviated Scale of Intelligence
WIAT—Wechsler Individual Achievement Test

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Address correspondence to William T. Mahle, MD, Children's Healthcare of Atlanta, Emory University School of Medicine, 1405 Clifton Rd, NE, Atlanta, GA 30322-1062. E-mail: mahlew@kidsheart.com

THE SURGICAL STRATEGIES for children with hypoplastic left heart syndrome (HLHS) include both infant heart transplantation and staged surgical reconstruction (Norwood procedure). Although the latter approach is used more commonly because of limited numbers of infant heart donors, both approaches have resulted in dramatic improvements in survival rates for these children. Two series reported 5-year survival rates of 72% after staged reconstruction[1] and 76% after infant heart transplantation.[2] Tempering these data, however, have been reports of neurodevelopmental deficits among survivors of either palliative approach. Generally, single-center series have reported mild to moderate cognitive deficits.[3–7] Recent data suggested that a variety of factors related to cardiovascular anatomic features and prenatal hemodynamics might play important roles in neurodevelopmental outcomes for these patients.[8,9] It is not known, however, whether one surgical strategy, ie, transplantation or the Norwood procedure, might result in more favorable outcomes. An examination of the neurodevelopmental outcomes of school-aged survivors of the 2 approaches with a standardized battery of developmental tests could provide unique insight into the factors that influence later cognitive function among children with HLHS.

METHODS

Study Design

Previously, we reported a multi-institutional analysis of risk factors for survival after the Norwood procedure or primary heart transplantation at 4 centers.[10] The same 4 centers participated in a cross-sectional evaluation of school-aged children who had undergone either the Norwood procedure or transplantation. These institutions were Children's Healthcare of Atlanta, Children's Hospital Boston, Loma Linda University Children's Hospital, and St Louis Children's Hospital. Of the 4 centers, 1 used a uniform strategy for transplantation, 1 offered staged reconstruction (Norwood procedure), and 2 performed both transplantation and staged reconstruction, transitioning to staged reconstruction partly because of limited donor availability.

Patient Population

A cross-sectional study was performed between July 2003 and September 2004, to include all school-aged survivors of staged reconstruction or primary heart transplantation for treatment of HLHS at the 4 institutions. Patients were identified as part of a broad research project examining various outcome measures among children with HLHS. HLHS was defined as normal segmental anatomic features with mitral and/or aortic atresia or stenosis and a left ventricle too small to sustain the systemic circulation. Patients with HLHS who were born before January 1, 1994, with birth weights of ≥2 kg, at 37 to 42 weeks of gestation, and were admitted to the surgical center with the intention that surgery would be performed were included. Patients with HLHS who had other congenital cardiac malformations, such as anomalous pulmonary venous return, transposition of the great arteries, ventricular septal defect, or double-outlet right ventricle, were excluded. Infants with major noncardiac malformations and chromosomal abnormalities were also excluded. The protocol was approved by the institutional review boards of all 4 institutions; consent and, where appropriate, assent were obtained from all participants.

Medical History

Medical records, operative notes, and perfusion data were reviewed for all enrolled subjects. Socioeconomic status was determined with a 2-factor equation including household income and maternal education, with a range of 34 to 77.[11] Variables considered to be potential predictors of neurocognitive outcomes were assessed (Table 1).

Developmental Testing

Formal tests of neurocognitive outcomes were administered by neuropsychologists (K.J.V., S.M.K., M.C.F., and W.G.H.). The tests were administered at a single morning session.

Cognitive Testing

The Wechsler Abbreviated Scale of Intelligence (WASI) was administered to assess cognitive function. The WASI is a screening measure of intellectual functioning. The scales are composed of 4 subtests and yield full-scale, verbal, and performance IQ scores (expected mean: 100 ± 15).

Achievement Testing

Subjects were evaluated with the Wechsler Individual Achievement Test, Second Edition (WIAT-II). The tests assess academic performance in basic reading, spelling, and mathematics reasoning and are scaled with a mean of 100 ± 15.

TABLE 1 **Variables Analyzed for Association With Neurodevelopmental Outcomes**

Patient-Related	Procedure-Related
Birth weight	Age at surgery
Apgar scores	DHCA duration
Metabolic acidosis (pH < 7.1)	Cardiopulmonary bypass duration
Cardiac arrest	Cooling temperature
Preoperative clinical seizures	Length of stay
Serum creatinine concentrations	Postoperative length of stay
Ascending aorta dimensions	
Aortic atresia	
Socioeconomic status	
Grade of tricuspid insufficiency	

Language Testing

Language skills were assessed with the Clinical Evaluation of Language Fundamentals, Third Edition (CELF-III). Both receptive and expressive language skills are evaluated, and standard scores are calculated from 3 subtests (mean: 100 ± 15).

Tests of Motor Function

The Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI), Fifth Edition, was used to assess visual-spatial and visual-motor integration ability (mean: 100 ± 15).

Assessment of Behavior Problems and Competencies

The parents were asked to complete 2 batteries, the Behavior Rating Inventory of Executive Function (BRIEF) and the Behavior Assessment System for Children (BASC). The BRIEF consists of a single rating form that is used by parents to rate a child's executive functions within the context of his or her everyday environments. BRIEF scores are age- and gender-standardized *T* scores with a mean of 50 ± 10, with higher scores reflecting greater executive dysfunction. Scores of ≥65 (eg, ≥1.5-fold above the normative mean) are considered to be abnormally elevated and to represent clinically significant behavior problems. The BASC is an instrument for evaluating the behavior of children 4 to 18 years of age. In this study, the rating scale for parents was used; it measures numerous aspects of behavior and personality, including positive (adaptive) and negative (clinical) dimensions. Adaptive composite *T* scores of ≤30 and clinical composite *T* scores of ≥70 are clinically significant.

Statistical Analyses

Comparisons between data for the cohort of patients with HLHS and published normative data were performed with a 1-sample *t* test. Comparisons between the Norwood procedure group and the transplantation group were performed with a 2-tailed Student's *t* test for continuous variables and a χ^2 test or Fischer's exact test for categorical variables. Analysis of the potential predictors of neurocognitive outcomes and the psychometric test scores was performed with stepwise multiple linear regression. We used stepwise selection, with the order of entry being variables with the largest coefficient of determination through to those with the smallest and with removal of variables with minimal ability to explain the variability in the outcome measure. Statistical significance was determined at *P* values of <.05.

RESULTS

Patient Population

There were 153 subjects with HLHS who had undergone either primary transplantation or the Norwood procedure who had been discharged to home and were thought to be alive at the time of the last contact from the institution. Many of these subjects had not been contacted for several years. There were 39 subjects who lived far from the site of their infant surgical palliation and were not considered for evaluation. Of the remaining 114 eligible subjects, there were 22 subjects (19%) for whom the current address or status could not be confirmed; the previously reported address was no longer correct. There were 25 subjects (22%) who did not respond to 3 letters of invitation to participate. There were 19 subjects (17%) who declined to participate in the study. There were, therefore, 48 subjects (42%) who participated in the study. The participation rates for the transplantation and Norwood procedure groups were not significantly different (42% and 38%, respectively; $P = .54$). We compared a number of other variables between subjects who participated in neurodevelopmental testing and other intermediate-term survivors from our study population, to assess for selection bias. There was no significant difference between these subjects with respect to insurance status ($P = .66$), gender ($P = .30$), presence of aortic atresia ($P = .23$), length of hospital stay ($P = .95$), or birth weight ($P = .89$).

Of the 48 subjects who participated in the study, 25 had undergone the Norwood procedure. A subsequent superior cavopulmonary anastomosis was performed for 21 subjects (84%), and all 25 subjects underwent a lateral-tunnel Fontan procedure. Twenty-two subjects underwent primary heart transplantation. One subject underwent the Norwood procedure in infancy and subsequently underwent heart transplantation because of ventricular dysfunction. This subject was included in the Norwood procedure group for analyses. One transplant patient did not complete any psychometric tests because of reported fatigue. The mean age of these children at the time of developmental evaluation was 12.4 ± 2.5 years (range: 8.0–17 years).

There were no significant differences between the transplant and Norwood procedure patients with respect to family income or parental education (Table 2). A higher percentage of the Norwood procedure patients were male. The transplant patients had significantly shorter duration of cardiopulmonary bypass and a higher core cooling temperature at the time of surgery than did the Norwood procedure patients. The transplant patients were also older at the time of surgical intervention, with a median age of 27 days, compared with 6 days for the Norwood procedure population. The median length of hospital stay was longer for the transplantation group than for the Norwood procedure group (46 days and 25 days, respectively).

Standardized Psychometric Testing

Forty-seven subjects completed the WASI. The WIAT-II was completed by 46 subjects, the VMI test by 42 sub-

TABLE 2 **Patient Characteristics**

	Norwood Procedure ($n = 26$)	Transplant ($n = 21$)	*P*
Patient-related			
Age at testing, y	12	12.9	.22
Male gender, %	81	50	.02
Race, nonwhite, %	12.5	11.8	.95
Insurance private/HMO, %	79	91	.28
Parents married, %	77	80	.81
Mean family income	$60 000–80 000	$40 000–60 000	.58
Mother's education level	Some college	Some college	.44
SES score	66.1	65.5	.76
Special education, %	54	55	.94
Learning delay reported by parents, %	50	35	.32
Birth weight, kg	3.52	3.56	.75
Aortic atresia, %	56	69	.43
Preoperative seizure, %	6	17	.36
Procedure-related			
Age at first operation, median, d	6	27	<.001
Cardiopulmonary bypass time, min	99	80	.02
DHCA time, min	59	52	.04
Cooling temperature, °C	14.7	18.5	<.001
Total length of stay, median, d	25	46	<.001

Values are expressed as mean (or median, where appropriate). HMO indicates health maintenance organization; SES, socioeconomic status.

jects, the CELF-III by 41 subjects, the BRIEF by 46 subjects, and the BASC by 44 subjects. The results of psychometric testing for the 2 patient groups are shown in Table 3. The mean scores for the entire cohort for all subtests of the WASI, CELF-III, WIAT, and VMI test were significantly below population normative values ($P < .01$ for all measures). The mean full-scale IQ (WASI Full-4 IQ) for the entire cohort was 86 (range: 57–115). The mean test scores for intelligence, achievement, and language skills ranged between 80 and 93, with the exception of CELF-III expressive language scores, which were 76 ± 17 for the transplantation cohort. The scores for the Beery-Buktenica VMI evaluation were also lower than those for other domains, with mean VMI test scores of 75 ± 16 and 77 ± 12 for the Norwood procedure and transplant patients, respectively.

Predictors of Neurodevelopmental Outcomes

Analyses were performed to determine which patient-related and procedure-related variables were associated with IQ and achievement scores for the patients who participated in standardized testing. Surgical strategy (transplantation versus Norwood procedure) was not associated with any developmental test scores in multi-

TABLE 3 **Comparison of Neurodevelopmental Testing Results**

	Entire Cohort ($n = 47$)	Norwood Procedure ($n = 26$)	Transplant ($n = 21$)	*P*[a]
Verbal IQ	88 ± 15	93 ± 15	84 ± 13	.04
Performance IQ	85 ± 16	87 ± 17	82 ± 15	.34
Full-scale IQ[b]	86 ± 14	89 ± 15	82 ± 13	.14
CELF-III Receptive	84 ± 18	88 ± 19	80 ± 16	.16
CELF-III Expressive	81 ± 18	85 ± 18	76 ± 17	.11
WIAT Math Reasoning	89 ± 21	91 ± 20	86 ± 21	.33
WIAT Basic Reading	89 ± 14	91 ± 12	87 ± 16	.34
WIAT Spelling	89 ± 14	88 ± 13	91 ± 15	.46
VMI test	76 ± 14	75 ± 16	77 ± 12	.64
BRIEF Behavior Regulation[c]	54 ± 12	56 ± 13	53 ± 12	.38
BRIEF Metacognition[c]	57 ± 11	57 ± 11	57 ± 11	.91
BRIEF Global Executive[c]	57 ± 11	57 ± 11	56 ± 11	.86
BASC Externalizing[c]	48 ± 10	51 ± 10	46 ± 10	.12
BASC Internalizing[c]	54 ± 11	54 ± 11	54 ± 11	.99
BASC Behavioral Symptoms[c]	52 ± 11	53 ± 11	50 ± 12	.29
BASC Adaptive Skills[c]	46 ± 11	48 ± 12	43 ± 10	.13

Values are expressed as mean ± SD.

[a] Comparing transplant and Norwood procedure groups.

[b] Full-4 IQ.

[c] Data are reported as *T* scores.

variate analyses. After adjustment for race and socioeconomic status in multivariate analyses, only prolonged hospital stay was associated with lower full-scale IQ scores (Table 4). Subjects with hospital stays of >40 days had a median full-scale IQ of 78, compared with a full-scale IQ of 92 for those with stays of <40 days ($P = .003$) (Fig 1). Longer total lengths of stay were also associated with lower verbal IQ (coefficient: −0.26; $P = .01$), lower performance IQ (coefficient: −0.32; $P = .01$), and lower WIAT-II mathematics reasoning subtest scores (coefficient: −0.34; $P = .02$). The presence of an atretic aortic valve was associated with lower math achievement test scores (coefficient: −15.6; $P = .02$). Other procedure-related factors, such as duration of cardiopulmonary bypass or deep hypothermic circulatory arrest (DHCA), were not associated with developmental outcomes. The surgical strategy was not associated significantly with either BRIEF or BASC scores.

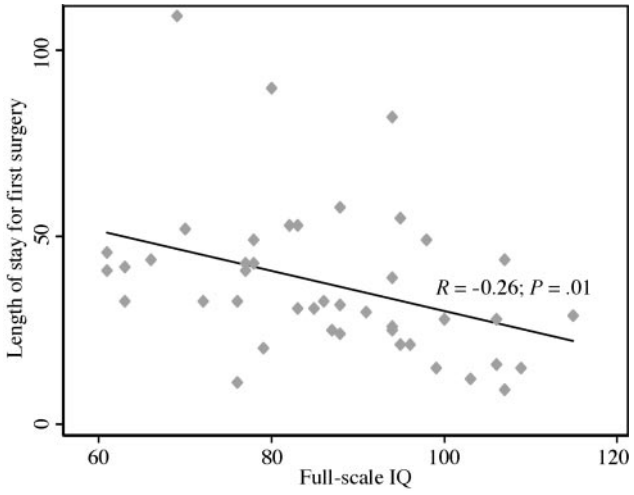

FIGURE 1
Plot of full-scale IQ scores on the *x*-axis and total length of hospital stay (in days) on the *y*-axis.

DISCUSSION

This study reports the neurodevelopmental outcomes of a cohort of school-aged children with HLHS who underwent either primary heart transplantation or staged reconstruction with the Norwood procedure. This cohort of children with HLHS demonstrated mean developmental test scores below the published population normative values in all cognitive domains. There was no significant difference in outcomes based on surgical strategy. Prolonged hospitalization at the time of the Norwood procedure or heart transplantation was predictive of measures of intelligence and achievement.

The results from standardized psychometric testing yielded scores similar to those in previously published reports that evaluated children with HLHS. The initial studies examining children with HLHS who had undergone the Norwood procedure reported that many (the majority, in some cases) subjects had severe developmental delays.[12,13] A number of more-recent, larger, single-institution studies generally found that mean full-scale IQ scores were in the range of the middle 80s to low 90s, suggesting that the majority of children with HLHS have mild impairments.[4,6,7] Mahle et al[6] reported a median full-scale IQ of 87 among 28 school-aged children with HLHS who had undergone staged palliation. Kern et al[7] reported on a younger cohort of children who underwent staged reconstructive surgery in the 1990s. Standardized tests for these 14 patients revealed a median full-scale IQ of 88 and a median adaptive behavior score of 91 (expected value for both: 100). In addition, in comparison with their siblings, the patients with HLHS also scored lower on the Vineland Adaptive Behavior Scales. Goldberg et al[4] reported the neurodevelopmental outcomes for patients with single ventricle who underwent surgery between 1991 and 1996. The median full-scale IQ for patients with HLHS ($n = 26$) was 94, although this was significantly lower than that reported for the non-HLHS, single-ventricle group ($n = 25$; mean full-scale IQ: 107).

Infant heart transplantation has been undertaken in many centers as a treatment strategy for HLHS. Transplantation is used less often than the Norwood procedure, in large part because of the scarcity of potential donors. As with the Norwood procedure, infant transplantation for treatment of HLHS is often performed with circulatory arrest. Ikle et al[5] evaluated the neurodevelopmental status of 26 preschool-aged and school-aged children treated for HLHS with heart transplantation. For patients who were >36 months of age at the time of testing, the mean full-scale IQ score was 88.5.[5] The mean performance and verbal IQ scores were 89.9 and 90.5, respectively. For patients who were <36 months of age, the median Mental Developmental Index score was 88 and the median Psychomotor Developmental Index score was 86.5. More recently, Baum et al[3] reported the neurologic outcomes for 55 school-aged

TABLE 4 **Relationship of Patient- and Procedure-Related Factors to Full-Scale IQ**

	Univariate		Multivariate[a]	
	Coefficient	*P*	Coefficient	*P*
Norwood procedure	6.27	.14		
Birth weight	−4.9	.31		
Preoperative seizure	−8.07	.29		
Cardiopulmonary arrest	−1.35	.76		
Age at surgery	−0.14	.24		
Aortic atresia	−5.26	.28		
Cardiopulmonary bypass time	−0.04	.61		
DHCA time	0.04	.83		
Arrest temperature	−0.08	.29		
Length of stay	−0.27	.01	−0.31	.004
Postoperative length of stay	−0.27	.08		

[a] Adjusted for race, parental education, and socioeconomic status.

patients (>5 years of age) who had undergone infant heart transplantation, the majority (75%) of whom had HLHS. The mean full-scale IQ score in that series was 81 ± 19, below expected population normative values. Prolonged hospitalization, duration of cardiopulmonary bypass, and socioeconomic factors were associated with cognitive deficits.

In addition to evaluating global cognitive function, we examined several specific neurodevelopmental domains. As with measures of intelligence, the test scores for language assessment and visual-motor integration were below population normative values. The measures of receptive and expressive language tended to be slightly lower than the measures of achievement or intelligence. A previous study by Mahle et al[6] suggested that school-aged children with HLHS had the greatest deficits in the area of language. In that study, the mean receptive and expressive language scores on the CELF-Revised were 76 and 78, respectively. Similarly Baum et al[3] reported significant language deficits in their cohort of infant transplant patients; the mean scores were identical to those found by Mahle et al.[6] One possible explanation for why children with HLHS might be at high risk for language delay is that they are hospitalized (sometimes for long periods) in infancy, when many language skills are acquired. We also noted greater deficits in visual-motor integration. A number of other investigators have identified prominent deficits in visual-motor and visual-spatial domains among children with HLHS and other congenital heart lesions.[3,7,14] An association between the use of DHCA and visual-spatial deficits was reported for children with transposition of the great arteries.[14]

A variety of patient- and procedure-related factors for neurodevelopmental delay have been identified in the HLHS population. Numerous studies performed with human subjects and animals suggested that extended periods of DHCA are associated with subsequent neurologic injury, although the relationship between cognitive impairment and duration of DHCA is not linear.[14,15] With current bypass techniques, the risk of neurologic compromise increases when the duration of DHCA exceeds ~40 minutes.[14] Kern et al[7] reported that the duration of DHCA at the time of the Norwood procedure was associated inversely with subsequent developmental test scores in their series. In our study, duration of DHCA at the time of the Norwood procedure or transplantation was not predictive of full-scale IQ scores. The mean duration of DHCA was 59 minutes for the Norwood procedure and 52 minutes for heart transplantation. Other intraoperative factors, such as core cooling temperature and duration of cardiopulmonary bypass, also were not predictive of outcome measures. The 4 centers used a variety of approaches to intraoperative management, including acid-base management, hematocrit adjustment, and cooling. Such variation limits our ability to identify the potential effects of a single intraoperative variable, such as duration of DHCA, on outcomes.

Prolonged hospital stays at the time of the Norwood procedure or transplantation were associated with poor outcomes. Subjects with hospital stays of >40 days had a median full-scale IQ of 78, compared with 92 for subjects who were discharged within 40 days after admission. Previous investigators found an association between length of hospital stay and neurodevelopmental outcomes.[3,16,17] Examining children with transposition of the great arteries who underwent arterial switch and were evaluated subsequently at 8 years of age, Newburger et al[16] reported that each additional 1 day of hospital stay led to a reduction of 0.9 points in full-scale IQ scores. Similarly, Limperopoulos et al[18] demonstrated that longer durations of hospital stay were associated with lower scores on the Griffiths Mental Developmental Scale and a higher prevalence of neurologic abnormalities in a cohort of infants with a variety of congenital heart lesions. The mechanism through which length of stay affects subsequent developmental outcomes is not fully understood. Presumably length of stay is a surrogate marker for events the result in neurologic injury. In addition, feeding difficulties are a common complication after transplantation or the Norwood procedure and often result in delayed hospital discharge.[19] Such difficulties may be related in part to early neurologic deficits.[20] Ikle et al[5] reported that patients who waited longer for transplantation had significantly lower scores in cognitive testing; they estimated a 4.5-point decrease in IQ for each 1 month on the waiting list. We did not identify the same association, although the mean waiting time to transplantation was only 29 days in our series, compared with 3 months reported by Ikle et al.[5]

One of the important findings of this study is that the approach to palliation (transplantation versus Norwood procedure) does not seem to influence significantly the developmental outcome for children with HLHS. This may simply reflect the fact that, with both strategies, complex neonatal surgery is required and postoperative hemodynamics may be marginal. Alternatively, it is possible that preoperative and even prenatal factors may be the major determinants of late neurologic status. Donofrio et al[9] reported elevated cerebral vascular resistance among fetuses with obstructive left heart lesions and found that cerebral vascular resistance was related inversely to in utero head growth. Cerebral blood flow is known to be impaired among neonates with HLHS before surgical intervention.[21] At birth, neonates with HLHS have a prevalence of microcephaly that exceeds 20% in some series.[22] One preliminary report suggested that the severity of ascending aorta hypoplasia was correlated directly with the degree of microcephaly.[23] These data are of particular interest because we found an association between the presence of aortic atresia and lower math achievement test scores. In addition, neuro-

imaging studies have shown ischemic insults and elevation of brain lactate levels before surgical intervention.[24] It seems likely, therefore, that these preoperative factors may account, at least in part, for the finding that patients with HLHS have poorer developmental outcomes than do subjects with other single-ventricle lesions.[4,15]

Although this represents the largest report of developmental outcomes for school-aged children with HLHS, the study lacked sufficient power to detect modest (but potentially clinically significant) differences between the 2 study populations. An enrollment population of 127 subjects would be needed to exclude a 5-point difference in full-scale IQ scores. In addition, there were a significant number of eligible subjects who did not participate in the study. We cannot exclude a selection bias in the tested cohort, although the enrolled and nonenrolled subjects did not differ in a number of key variables. Moreover, the study excluded certain high-risk patients, such as those with low birth weight, and the data may not be generalizable to such high-risk patients with HLHS. Lastly, the risk factor analysis focused on the initial palliative procedure, ie, Norwood procedure or transplantation. Patients who underwent the Norwood procedure had additional cavopulmonary surgery with cardiopulmonary bypass. Because of the small number of subjects in the present study, a detailed investigation of potential risk factors from these additional operations was not considered in our analysis.

CONCLUSIONS

Neurodevelopmental deficits are prevalent, although generally mild, among school-aged children with HLHS, regardless of the initial palliative strategy. A prolonged hospital stay at the time of initial palliation was associated with poorer neurodevelopmental outcomes at school age. Ongoing evaluation of children with HLHS is warranted, especially in light of recent modifications such as regional cerebral perfusion, a right ventricle-to-pulmonary artery-type Norwood procedure, and transcatheter interventions that avoid the need for prolonged prostaglandin therapy while heart transplantation is awaited.

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