



Total Serum Bilirubin within 3 Months of Hepatoportoenterostomy Predicts Short-Term Outcomes in Biliary Atresia

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Objectives To prospectively assess the value of serum total bilirubin (TB) within 3 months of hepatoportoenterostomy (HPE) in infants with biliary atresia as a biomarker predictive of clinical sequelae of liver disease in the first 2 years of life.

Study design Infants with biliary atresia undergoing HPE between June 2004 and January 2011 were enrolled in a prospective, multicenter study. Complications were monitored until 2 years of age or the earliest of liver transplantation (LT), death, or study withdrawal. TB below 2 mg/dL (34.2 μ M) at any time in the first 3 months (TB <2.0, all others TB \geq 2) after HPE was examined as a biomarker, using Kaplan-Meier survival and logistic regression.

Results Fifty percent (68/137) of infants had TB <2.0 in the first 3 months after HPE. Transplant-free survival at 2 years was significantly higher in the TB <2.0 group vs TB \geq 2 (86% vs 20%, $P < .0001$). Infants with TB \geq 2 had diminished weight gain ($P < .0001$), greater probability of developing ascites (OR 6.4, 95% CI 2.9-14.1, $P < .0001$), hypoalbuminemia (OR 7.6, 95% CI 3.2-17.7, $P < .0001$), coagulopathy (OR 10.8, 95% CI 3.1-38.2, $P = .0002$), LT (OR 12.4, 95% CI 5.3-28.7, $P < .0001$), or LT or death (OR 16.8, 95% CI 7.2-39.2, $P < .0001$).

Conclusions Infants whose TB does not fall below 2.0 mg/dL within 3 months of HPE were at high risk for early disease progression, suggesting they should be considered for LT in a timely fashion. Interventions increasing the likelihood of achieving TB <2.0 mg/dL within 3 months of HPE may enhance early outcomes. (*J Pediatr* 2016;170:211-7).

Trial registration ClinicalTrials.gov: NCT00061828 and NCT00294684.

Although biliary atresia (BA) is a rare disorder occurring between 1 in 8000 and 1 in 18 000 live births, nearly one-half of affected children will require liver transplantation (LT) within the first 2 years of life. An additional 20%-30% will require LT in childhood and adolescence. Consequently, BA is the leading indication for LT in childhood, accounting for nearly 35% of pediatric LT (based upon Organ Procurement and Transplantation Network data as of February 16, 2015¹). The underlying cause(s) and mechanisms of progression of this fibroinflammatory obliterative cholangiopathy are unknown. The sole intervention that has been shown to affect survival with native liver is the hepatoportoenterostomy (HPE), commonly referred to as the Kasai procedure since it was

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AUC	Area under the curve
BA	Biliary atresia
ChILDRen	Childhood Liver Disease Research Network
HPE	Hepatoportoenterostomy
LT	Liver transplantation
PROBE	Prospective Database of Infants with Cholestasis
ROC	Receiver operating characteristic
START	Steroids in Biliary Atresia Randomized Trial
TB	Total bilirubin

first described by Morio Kasai.² In cases where the HPE is ineffective in restoring bile flow, there is rapid progression to biliary cirrhosis, liver failure, and death by 2-3 years of age.³ Though LT is an excellent option to restore health, prediction of the need for and determining the optimal timing of LT are challenging. Predictors of outcomes in BA have been identified largely through single center studies or retrospective multicenter analyses.⁴⁻²¹ Despite BA becoming the focus of increased research activity in the past decade, prospective multicenter studies of clinical outcomes are limited.

This study reports findings of the Prospective Database of Infants with Cholestasis (PROBE) study undertaken by the 16 member institutions and investigators of the National Institutes of Diabetes, Digestive and Kidney Diseases of the National Institutes of Health-supported Childhood Liver Disease Research Network (ChiLDReN; formerly the Biliary Atresia Research Consortium). PROBE was designed to acquire longitudinal, prospective clinical and laboratory data in a standardized fashion at defined time points to enable definitive studies of natural history of cholestatic liver diseases in infants and early childhood. Here, we focus on the analysis of the outcomes of children with BA over the first 24 months of life and the laboratory and clinical markers that predict these near-term outcomes. We hypothesized that serum levels of total bilirubin (TB) in the first 3 months after HPE (as an indicator of successful bile drainage post-HPE) would be predictive of 2-year outcomes in children with BA.

Methods

Study participants included subjects enrolled in PROBE ([Clinicaltrials.gov](https://clinicaltrials.gov): NCT00061828), more than 2 years before the data cutoff date (ie, who had the potential for at least 2 years of follow-up). Informed consent was obtained from parents or guardians, and the protocol was carried out under institutional review board approval. Inclusion criteria for enrollment in PROBE included presentation prior to 180 days of age with cholestasis defined as serum direct or conjugated bilirubin greater than or equal to 2.0 mg/dL and greater than 20% of TB. Infants who had undergone previous hepatobiliary surgery with dissection or excision of biliary tissue before presentation at a ChiLDReN site were not eligible for PROBE. The study population for this report was further restricted to subjects with BA who underwent HPE. After September 1, 2005, PROBE participants with BA who underwent HPE were eligible to be co-enrolled in a prospective, randomized double-blinded, placebo-controlled trial of corticosteroid therapy after HPE for BA (Steroids in Biliary Atresia Randomized Trial [START]; [Clinicaltrials.gov](https://clinicaltrials.gov): NCT00294684). Participants co-enrolled in START (n = 135) were excluded from this analysis because they were the focus of a separate report.²² Corticosteroids were not typically employed as adjunctive therapy to HPE outside of START.

Data prospectively collected by study research coordinators and clinical investigators were entered into a centralized

database at the data coordinating center. Baseline data included demographics, medical and family history, and laboratory studies. Follow-up visits for data collection occurred at 1, 2, 3, and 6 months after HPE and at 12, 18, and 24 months of age.

Data Analyses

Descriptive data were summarized as the mean and SD for continuous variables and as percentages for categorical variables. In addition to the descriptive analysis of baseline variables, we evaluated the fidelity of TB as a marker of clinical outcomes at 3 months up to 2 years of age following surgical drainage. Outcomes of interest included survival with native liver and complications of advancing liver disease, including manifestations of portal hypertension. Response to HPE was dichotomized into 2 groups based upon TB levels in the first 3 months after HPE. TB <2.0 mg/dL (TB <2) was defined by any TB less than 2.0 mg/dL (34.2 μ M) within the first 3 months post HPE, and TB \geq 2.0 was defined as never achieving a TB less than 2.0 mg/dL in the first 3 months post-HPE.

Logistic regression was used to model the probability that a specific clinical event occurred at least once in the period beginning 3 months after HPE as a function of the TB dichotomy described above. The clinical end points of interest were development of ascites (deemed clinically significant and/or requiring ongoing diuretic therapy), variceal hemorrhage (gastrointestinal bleed confirmed on endoscopy), thrombocytopenia (platelet count <150 000 \times 10⁹/L), splenomegaly (spleen palpable more than 2 cm below the costal margin), hypoalbuminemia (serum albumin <3.0 gm/dL), hyponatremia (serum sodium <130 mmol/L), coagulopathy (international normalized ratio >1.5), weight-for-age z-scores (failure to thrive defined as a z-score < -2.5), height-for-age z-scores, mid-arm circumference z-scores, receiving a LT, and death. The number and proportion for each TB group is reported, as well as an OR, *P* value, and 95% CI. In addition, 2-year Kaplan-Meier survival curves were generated to examine the time course for these clinical outcomes for each TB group, starting at HPE. To determine the relationship of successful HPE drainage in the first 3 months with each outcome, in all the above analyses, participants who had experienced the outcome of interest or underwent transplant or died before 3 months after HPE were excluded from the analysis cohort. An event was defined as the first occurrence of the clinical end point, with subjects censored at the earlier of transplant or death (except for the transplant or death analysis, where this would be considered the end point), loss to follow-up, or the end of the data collection period (January 1, 2013).

To compare the mean time trajectories of weight z-score and height z-score between the 2 TB groups, we used a joint model of longitudinal and survival data with penalized B-splines^{23,24} to adjust for potential bias because of informative dropout caused by LT.²⁵ In addition, the same method was used to estimate the mean trajectories of TB in the 2 TB groups. This joint model corrects the bias caused by informative dropout

in a conventional longitudinal model. The receiver operating characteristic (ROC) area under the curve (AUC) (area under the ROC curve) for logistic models predicting transplant-free survival using different TB thresholds at 3 months and 6 months post-HPE was calculated and compared.²⁶

All analyses were performed using SAS/STAT (SAS Institute Inc. 2008. SAS/STAT 9.2 User's Guide; SAS Institute Inc, Cary, North Carolina).

Results

Three hundred twenty-four infants with BA were enrolled in PROBE between June 1, 2004, and January 1, 2011, of whom 187 were excluded from this analysis. One hundred thirty-five were also enrolled in START, 4 had laparoscopic HPE, 27 did not have an HPE procedure, and 21 had reasons prior to the 3 month post-HPE time point that precluded their inclusion in the final analysis (1 death, 3 LT, 7 withdrawn or lost to follow-up from the study, and 10 without TB measurements). One hundred thirty-seven participants (70 female) were available for analysis (82 white, 18 black, 12 Asian, 18 other race, and 4 unknown; 33 Hispanic). HPE was performed at a mean of 58.5 days (SD 20.7 days). Fourteen had BA splenic malformation as defined by the presence of polysplenia or asplenia.

Survival with Native Liver

At age 2 years, 73 children were alive with their native livers, 53 had undergone LT, 9 died without LT, and 2 were lost to follow-up. The TB <2.0 mg/dL by 3 months post-HPE criteria were met by 68 (50%) infants and 56 (82%) of these infants were alive with native liver at age 2 years (Table). In contrast, in the 69 infants in the TB ≥2 group, only 15 (22%) were alive with native liver at age 2 years. Clinical complications of advancing liver disease were observed in 11 of these 15 participants (ascites: 1, splenomegaly: 5, hypoalbuminemia: 3, thrombocytopenia: 8, failure to

thrive: 2, multiple complications: 9). By both logistic regression and log-rank test, death or LT within the first 2 years of life was more likely for those infants with TB ≥2 compared with infants with TB <2.0 (Table and Figure 1).

The ROC AUC for the logistic model using a TB threshold of 2.0 mg/dL at 3 months post-HPE was 0.80, indicating a good predictive power for assessing the probability of LT or death prior to transplant. We also evaluated the impact of using a few different TB values with an alternative threshold (1.5 mg/dL, 25.6 μM) and/or using TB values within the first 6 months after HPE for predicting outcomes. Using a TB threshold of 2.0 mg/dL at 6 months post-HPE did not improve the ROC significantly (AUC = 0.82, *P* = .412 compared with TB <2.0 mg/dL at 3 months). Using a TB threshold of 1.5 mg/dL at 3 months (AUC = 0.82, *P* = .443) also yielded similar results. Finally, using a TB threshold of 1.5 mg/dL at 6 months post-HPE (AUC = 0.87) did significantly improve the ROC (*P* = .012).

Manifestations of Progressive Liver Disease

Logistic regression analyses were performed for the selected end points in the first 2 years of life related to the TB status in the first 3 months after HPE. Infants with TB ≥2 were significantly more likely to subsequently develop failure to thrive (weight z-score <−2.5), hypoalbuminemia, coagulopathy, and ascites (Table). By Kaplan-Meier analysis, the likelihood of specific adverse clinical events in the first 2 years of life was significantly less in infants with TB <2.0, including thrombocytopenia, hypoalbuminemia, ascites, and coagulopathy (Figure 1). Notably, the development of hyponatremia (3.7% overall) and variceal hemorrhage (6.6% overall) were uncommon events in this cohort, and, thus, there was insufficient power for detecting statistically significant differences between the 2 TB groups. Screening endoscopy was not routine (4/137 subjects screened) so the presence of varices could not be used as a marker of portal hypertension.

Table. BA outcomes by 2 years of age

Outcome events	Number (%) of patients with event			OR and 95% CI for TB ≥2 vs TB <2 mg/dL	<i>P</i> value
	All BA (n = 137)	TB status by 3 mo after HPE			
		TB <2 mg/dL (n = 68)	TB ≥2 mg/dL (n = 69)		
Weight z-score < −2.5	28 (20.4%)	8 (11.8%)	20 (29.0%)	3.1 (1.2, 7.5)	.015
Height z-score < −2.5	26 (18.9%)	10 (14.7%)	16 (23.2%)	1.8 (0.7, 4.2)	.21
Mid-arm circumference z-score < −2.5	51 (37.2%)	24 (35.3%)	27 (39.1%)	1.2 (0.6, 2.4)	.64
Hypoalbuminemia (albumin < 3.0 g/dL)	46 (33.6%)	9 (13.2%)	37 (53.6%)	7.6 (3.2, 17.7)	<.0001
Coagulopathy (INR > 1.5)	26 (19.0%)	3 (4.4%)	23 (33.3%)	10.8 (3.1, 38.2)	.0002
Hyponatremia (Na < 130 mEq/L)	5 (3.7%)	1 (1.5%)	4 (5.8%)	4.1 (0.4, 37.9)	.21
Thrombocytopenia (Platelets <150 000/μL)	65 (47.5%)	32 (47.1)	33 (47.8)	1.03 (0.5, 2.0)	.93*
Splenomegaly	86 (62.8%)	48 (70.6)	38 (55.1)	0.5 (0.3, 1.03)	.062
Ascites	52 (38.0%)	12 (17.7%)	40 (58.0%)	6.4 (2.9, 14.1)	<.0001
Variceal hemorrhage	9 (6.6%)	5 (7.4%)	4 (5.8%)	0.8 (0.2, 3.0)	.71
LT	57 (41.6%)	10 (14.7%)	47 (68.1%)	12.4 (5.3, 28.7)	<.0001
Death	9 (6.6%)	2 (2.9%)	7 (10.1%)	3.7 (0.7, 18.6)	.11
Death or LT	66 (48.2%)	12 (17.7%)	54 (78.3%)	16.8 (7.2, 39.2)	<.0001

INR, international normalized ratio.

Bold indicates *P* value <.05.

*Note by Kaplan-Meier analysis, thrombocytopenia was more common for TB >2 (Figure 1).

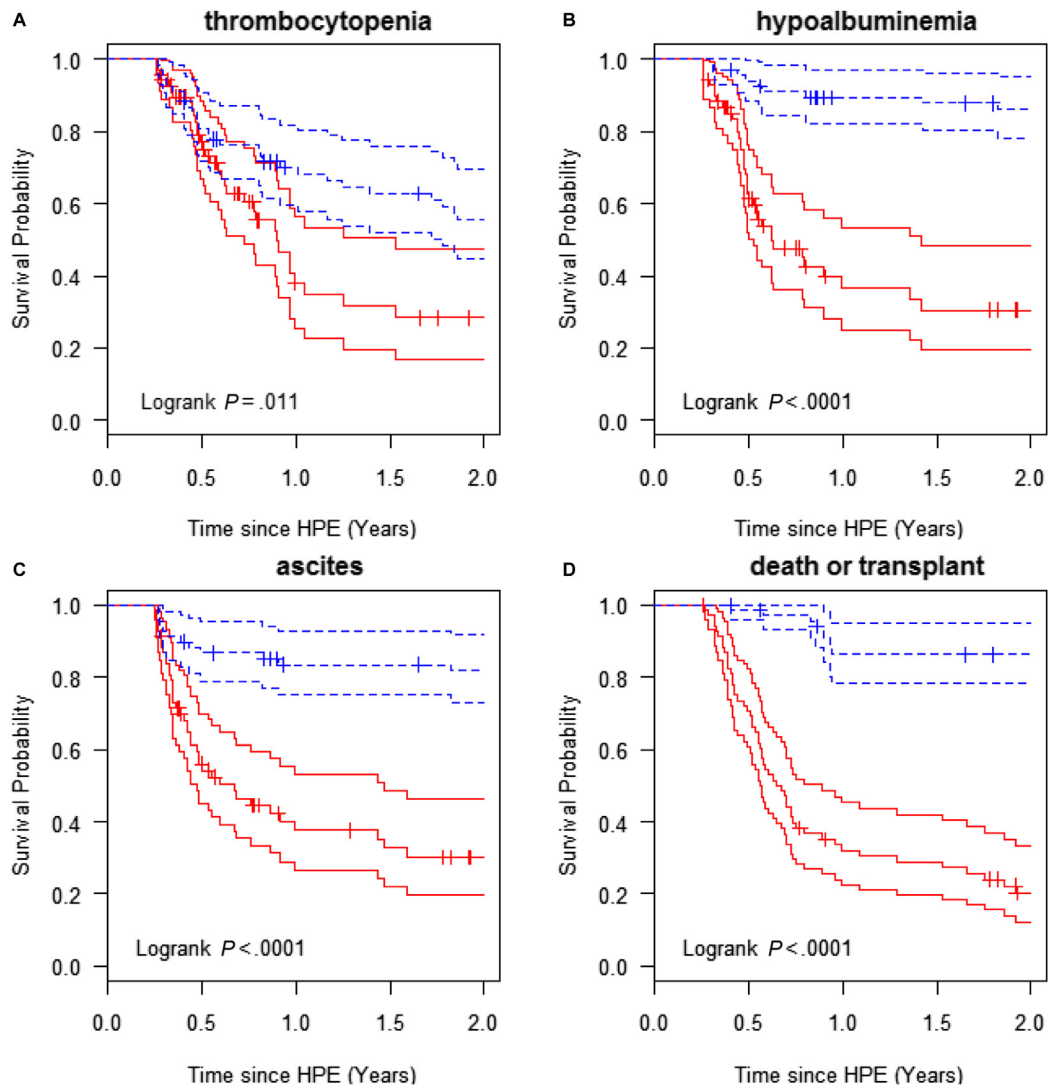


Figure 1. Kaplan-Meier estimate and its 95% CI for onset of specific clinical outcomes beginning 3 months after HPE in children who did (blue dashed lines) or who did not achieve a TB <2.0 mg/dL (red solid lines) in the first 3 months. Curves represent probability of remaining free of the clinical outcome. Rapid and clear differences were observed for **A**, thrombocytopenia, **B**, hypoalbuminemia, **C**, ascites, and **D**, death or LT. Time zero is the time of the HPE. Secondary lines surrounding primary data lines indicate 95% CIs.

Growth

Figure 2 shows the estimated growth curves of weight z-score and height z-score for infants with TB <2.0 compared with infants with TB ≥ 2 . Although the weight z-score in both groups of children decreased after HPE, children with TB <2.0 started to recover soon (about 1 month) after HPE, and their mean weight z-score was near 0.0 at 2 years of age. In contrast, the mean weight z-score in children with TB ≥ 2 dropped until about 3 months and remained approximately -1.5 through 2 years of age. The trajectories of weight z-scores of the 2 groups were significantly different from each other ($P < .0001$). The length z-score trajectory also differed significantly between the 2 groups ($P = .025$). Length z-score in infants with TB <2.0 improved linearly after HPE. In contrast, mean length

z-score in infants with TB ≥ 2 dropped until 6 months after HPE and started to improve after that, primarily because of censoring of those who died or underwent LT.

Stability of TB Status after HPE

To further investigate the utility of TB in the first 3 months after HPE as a predictive biomarker of 2-year clinical outcome, we analyzed all repeated measurements of TB up to 2 years of age (the duration of the study) (**Figure 3**; available at www.jpeds.com). Of the 68 infants with TB <2.0 mg/dL within the first 3 months, TB remained <2.0 mg/dL in 62 (91.2%) up to 2 years of age, and of the 69 with TB above 2.0 mg/dL, TB remained ≥ 2.0 mg/dL in 52 (75.4%) (**Figure 3**, A and B). The incidence of significant events correlated with TB status over the first

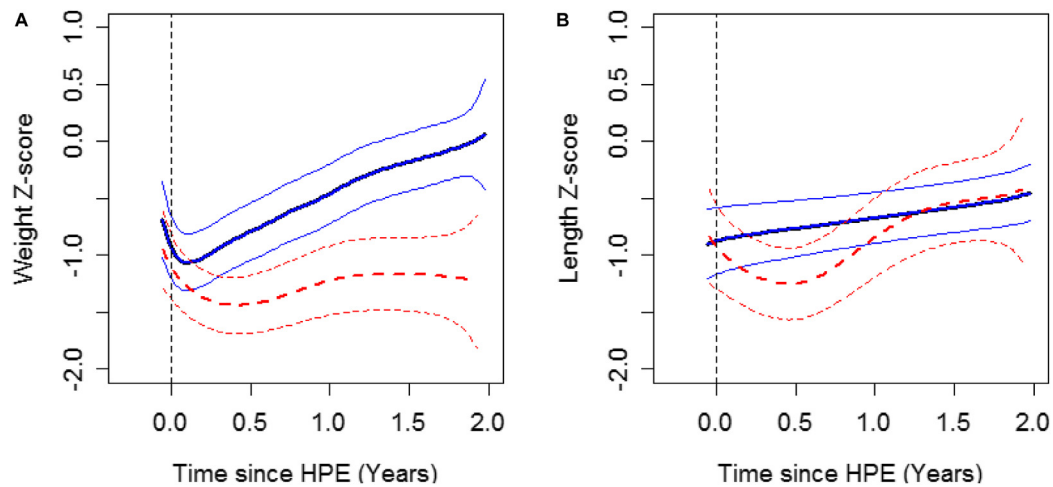


Figure 2. Growth curves plotting **A**, weight z-score and **B**, length z-score vs time since HPE. *Blue solid lines* (subjects who achieved a TB <2.0 mg/dL in the first 3 months after HPE) and *red dashed lines* (subjects who did not achieve a TB <2.0 mg/dL) represent the average value over time and its 95% CIs. The apparent improved length z-score after 1 year (*dashed line*) was due to censoring of those who died or underwent LT.

2 years of life. In the 52 subjects who never had a TB <2.0 mg/dL after HPE, 48 had an event (92%). In contrast, in the 62 subjects who persistently maintained at TB <2.0 mg/dL once attained, only 10 underwent LT (8) or died (2) within the first 2 years of life. In 23 infants, the TB crossed the 2.0 mg/dL threshold after 3 months post-HPE (Figure 3, C). Six in the TB <2.0 group subsequently had TB \geq 2.0 mg/dL prior to 2 years of age; 2 of these participants underwent LT prior to 2 years of age. Seventeen in the TB \geq 2 group subsequently had a TB <2.0 mg/dL. Four of these 17 underwent LT prior to 2 years of age. Thus, those with fluctuating TB levels had a course more consistent with the TB <2.0 group.

Discussion

Accurate early prediction of poor prognosis after HPE for BA permits focused anticipatory guidance and monitoring related to potential complications of advancing liver disease, implementation of prophylactic therapies and nutritional support, and early consideration of LT, especially living donor transplantation. The general importance of restitution of bile flow after HPE has been known for decades, although precision about this issue has not been the subject of detailed prospective investigation.^{27,28} In this large, prospective, and multicenter study, the simple parameter of TB within the first 3 months after HPE performs very well to predict outcome in the first 2 years of life. TB \geq 2.0 mg/dL by 3 months after HPE identifies the large majority of children who will die or require LT by 2 years of age and also predicts those who will develop early complications of chronic liver disease. These findings prospectively validate the results of our prior retrospective analysis.¹² The current study simplifies the predictor of outcome using a dichotomization relative to a TB of 2.0 mg/dL.

This multicenter series prospectively collected data on a contemporary group of children from the time of diagnosis of BA in a standardized manner, thereby allowing careful characterization of outcomes linked to early events. Single center studies have required 10-20 years to accumulate similar types of data.^{7,29} The enrollment of this cohort in 7 years with a 2-year outcome minimizes era effects in the interpretation of the data and the complications. The largest outcome study in France included patients diagnosed over more than a 20-year time interval,^{14,15,30,31} and studies in Finland, the United Kingdom, and The Netherlands accumulated patients over 10-20 years.^{14,15,30,31} Unlike retrospective analyses, clinical events in this study were defined a priori by agreed upon criteria and were prospectively identified, thus enhancing accurate collection of complications and minimizing bias. Previous studies have typically reported normalization of TB (<20 μ M) at 6 months after HPE and have correlated this with survival with native liver. Those studies have not systematically assessed the predictive value of this finding relative to complications of progressive liver disease nor variation of TB measurements over time.

LT can be a problematic end point, when TB is used as a biomarker of outcome as the timing of LT is somewhat subjective. Some clinicians believe that LT is indicated in infants with an unsuccessful HPE, given the poor prognosis associated with lack of bile drainage in BA, and, thus, TB could be, a self-fulfilling prophecy, strongly correlated with LT.^{32,33} One of the major strengths of the current study is that it demonstrates that TB \geq 2.0 mg/dL predicts other adverse clinical outcomes related to advancing liver disease, such as growth failure, ascites, or hypoalbuminemia, thereby supporting the potential role of TB as an important biomarker of 2-year outcome.

Despite the frequent findings of features of portal hypertension in this entire cohort, variceal hemorrhage was

uncommon in either TB group by 2 years of age, occurring in only 6.6% of participants. Moreover, variceal hemorrhage episodes were not fatal in any of the infants with BA in this series. This is in contrast to recent reports highlighting a relatively high frequency of esophageal varices in infants with BA and the potential need for primary endoscopic prophylaxis of varices in infants with BA.^{34,35} It is possible that the use of early LT may have altered the natural history of gastrointestinal bleeding in these patients compared with other studies. In a program using primary prophylaxis of varices, a total serum bilirubin $>40 \mu\text{M}$ at 6 months after HPE predicted subsequent presence of and bleeding from esophageal varices, which supports the importance of bile flow as a predictor of progressive liver disease.³⁶

TB measurement within the first 3 months of HPE is a stable predictive biomarker. In those infants with fluctuating levels, clinical outcomes were more consistent with the low TB group. Somewhat improved prediction of survival with native liver can be achieved using a TB cut-off of 1.5 mg/dL over the 6 months after HPE. However, waiting until 6 months after HPE may diminish the ability to preempt the development of serious complications (Figure 1). In practice, it would be reasonable to consider LT evaluation in infants with BA whose TB does not fall below 2.0 mg/dL in the first 3 months after HPE (Figure 4). LT might be reconsidered in the small number of these infants, whose

TB subsequently falls below 1.5 mg/dL in the first 6 months after HPE.

In conclusion, we have demonstrated in a prospective, multicenter study of a large cohort of infants with BA that failure to achieve a TB of $<2.0 \text{ mg/dL}$ in the first 3 months after HPE is associated with a high risk of complications of progressive liver disease and subsequent death or need for LT in the first 2 years of life. Conversely, infants who achieve at least 1 TB of $<2.0 \text{ mg/dL}$ within 3 months of HPE have a moderate risk of developing features of portal hypertension but have a significantly reduced risk of complications of progressive liver disease, LT, or death events by 2 years of age. The OR of death or transplant within the first 2 years of life for those with TB ≥ 2.0 vs $<2.0 \text{ mg/dL}$ in the first 3 months post-HPE was 16.8. We propose that TB should be consistently determined in the first 6 months following HPE, and results should be interpreted using a threshold of 2.0 mg/dL ($34.2 \mu\text{M}$; Figure 4). Families of those infants whose TB does not fall below 2 mg/dL in the first 3 months after HPE should receive enhanced anticipatory guidance about complications of end-stage liver disease. Intensive nutritional monitoring and interventions may be warranted, especially in light of the high risk of failure to thrive and fat soluble vitamin insufficiencies in infants with poor bile flow after HPE.^{37,38} In addition, these infants might be considered for relatively pre-emptive living donor LT potentially avoiding long-term sequelae and potential mortality associated with advancing disease. TB in the first 3 months is an appropriate biomarker and end point for future clinical trials of near-term outcomes in BA. Ongoing studies from ChiLDRen will further delineate the variables that impact TB within the 3 months after HPE. ■

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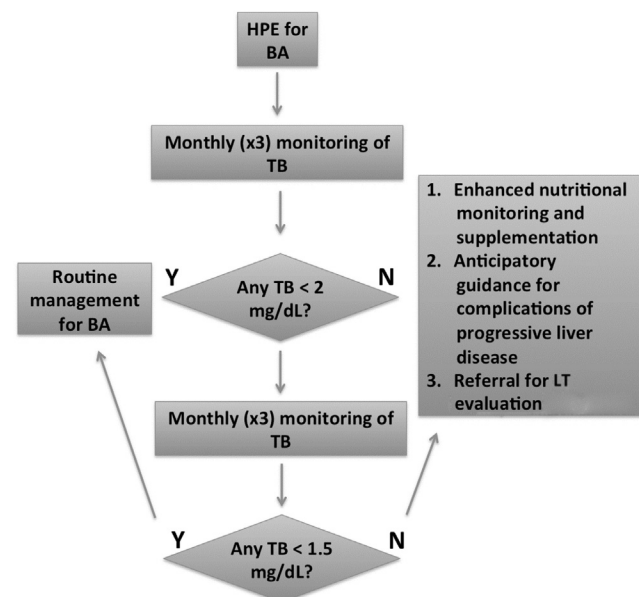


Figure 4. If the TB is found to be less than 2 mg/dL ($34.2 \mu\text{M}$) in the first 3 months, routine follow-up for BA is recommended. If not, heightened nutritional monitoring and supplementation, anticipatory guidance for potential complications of advanced liver disease, and LT evaluation is recommended. If in the subsequent 3 months the TB is found to be less than 1.5 mg/dL, candidacy for LT should be reassessed in the context of the clinical status of the infant.

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Appendix 1

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Appendix 2

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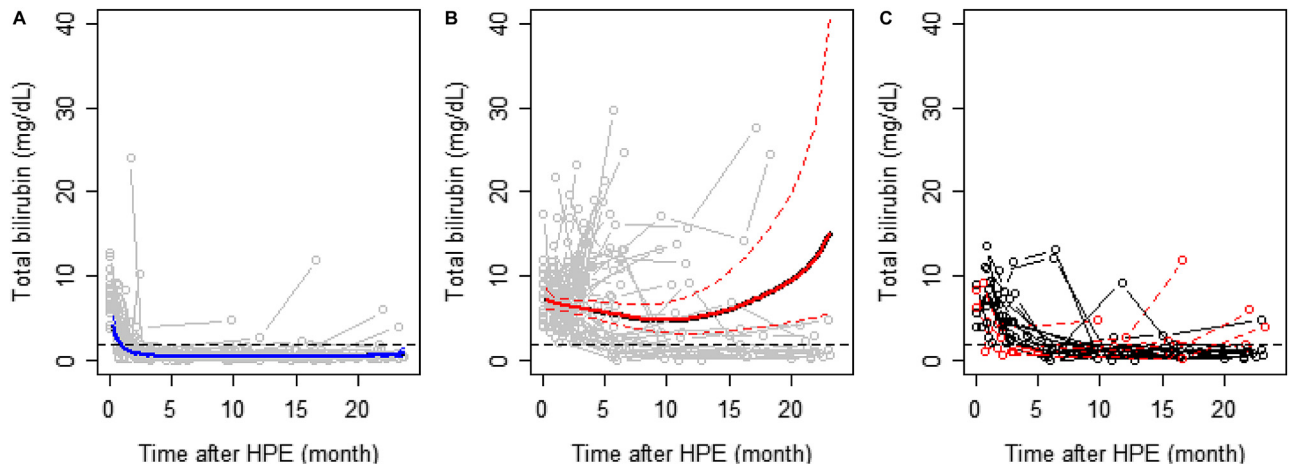


Figure 3. Trends in TB over time for children **A**, who achieved a TB <2.0 mg/dL in the first 3 months after HPE compared with those **B**, who did not. *Solid bold lines* represent the average value over time (*dotted lines* 95% CIs). *Gray open circles and lines* in both panels represent bilirubin trajectories for individual subjects. *Horizontal dashed line* indicates a TB of 2.0 mg/dL. Infants with BA generally maintain their group assignment defined at 3 months post-HPE. **C**, The trajectories of those that changed status after 3 months post-HPE.