

# TARGETED PREVENTION OF PEDIATRIC SHUNT INFECTION: DEVELOPMENT OF A USABLE RISK SCORE FOR LMIC SETTINGS

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## ABSTRACT

### **Background:**

Hydrocephalus is a major pediatric neurosurgical condition, particularly in low- and middle-income countries (LMICs), where shunt infection remains a major cause of morbidity and resource strain. Despite advances in shunt technology, infection rates remain 5–15%. This study aimed to identify modifiable risk factors for early postoperative infection and develop a pragmatic, point-based risk score for use in LMICs

### **Methods:**

We retrospectively analyzed 1,185 pediatric cerebrospinal fluid (CSF) shunt procedures performed at Lady Reading Hospital, Peshawar (2019–2024). Early infection ( $\leq 90$  days) was defined using CDC criteria. A matched case–control model (127 infections, 381 controls) and time-to-event analysis identified independent predictors. Logistic regression and bootstrap validation (500 resamples) assessed model performance. Regression coefficients were translated into an integer-based risk score.

### **Results:**

Early shunt infection occurred in 10.7% of cases, with a median onset of 21 days. Multivariable analysis identified five independent predictors: absence of an antibiotic-impregnated catheter (aOR 2.52, 95% CI 1.48–4.29), operative time  $>90$  min (aOR 2.10, 95% CI 1.22–3.62), prior external ventricular drain (aOR 1.89, 95% CI 1.18–3.02), low weight-for-age (aOR 1.85, 95% CI 1.12–3.06), and cloudy/purulent CSF at surgery (aOR 3.45, 95% CI 1.62–7.33). The internally validated model showed excellent discrimination (AUC = 0.83, Brier = 0.072). The derived score stratified infection risk as low (4.5%), intermediate (18.8%), and high (41.6%).

### **Conclusions:**

This study confirms established predictors and identifies new, practical markers nutritional status and intraoperative CSF clarity for early pediatric shunt infection. The derived, easy-to-use score enables targeted preventive strategies such as selective use of antibiotic-impregnated catheters or deferred surgery in high-risk children, optimizing outcomes and costs in resource-limited LMIC settings.

### **Keywords:**

Hydrocephalus, pediatric shunt infection, risk score, antibiotic-impregnated catheter, LMIC, neurosurgery, prevention.

## INTRODUCTION

Hydrocephalus is one of the most common pediatric neurosurgical disorders worldwide. It is estimated that ~400,000 new cases of childhood hydrocephalus occur globally each year [1], making shunt surgery one of the most frequently performed neurosurgical procedures [1]. However, only about half of implanted shunts remain functional at two years, and untreated hydrocephalus carries high morbidity and mortality [1]. In low- and middle-income countries (LMICs) such as Pakistan, the burden is especially high and resources (trained surgeons, specialized equipment) are limited [1]. In these settings, innovations (e.g. low-cost shunts) have emerged, but infection remains a major challenge [1].

Early postoperative shunt infection is a leading cause of shunt failure, morbidity, and prolonged hospitalization [2]. Reported infection rates in children undergoing ventriculoperitoneal shunt placement range from ~5-15% [3], with most infections occurring within the first two postoperative months [3]. Infected shunts can lead to ventriculitis, seizures, neurocognitive decline, and often require complete shunt removal or revision, imposing heavy clinical and economic costs [3,4].

Multiple pre- and perioperative factors have been implicated in pediatric shunt infection. Prior external ventricular drainage (EVD) or CSF drainage is known to elevate infection risk, likely due to colonization of hardware [3]. Long operative time and intraoperative breaches in sterility also favor bacterial contamination [3]. Conversely, antibiotic-impregnated shunt catheters (AICs) have been shown to roughly halve infection risk (pooled risk ratio  $\approx 0.46$ ) compared to standard systems [4]. Patient factors such as young age, immunodeficiency, and comorbidities (e.g. malnutrition, cardiac disease) also appear to predispose to infection [3,5]. However, available studies are heterogeneous and often from high-income settings; data from Pakistani or similar LMIC populations are scarce.

Given the persistent 5-15% infection rates despite modern techniques, a clearer understanding of specific risk factors in our setting is needed. Recent meta-analyses emphasize that identifying such factors is

“paramount to guiding preventive strategies” [3]. In particular, there has been interest in deriving risk scores to stratify patients and tailor interventions. A well-validated risk model could allow targeted use of costly measures (e.g. AICs) or timing adjustments (postponing surgery when CSF is not clear) in those at highest risk. In this study we retrospectively examined all pediatric CSF shunt surgeries over 8 years at a tertiary center in Khyber Pakhtunkhwa, Pakistan, to identify independent predictors of early ( $\leq 90$ -day) shunt infection. We then developed and internally validated a practical point-based risk score to stratify patients by infection risk. Our goal was to inform tailored prevention (such as selective AIC use or delayed shunting in the setting of abnormal CSF), especially in resource-limited settings where every intervention must be judiciously applied

## Materials and Methods

### Study Design and Setting

We conducted a retrospective, single-center study using data from all pediatric cerebrospinal fluid (CSF) shunt procedures performed at Lady Reading Hospital Peshawar, a tertiary neurosurgical referral center, between January 1, 2019, and December 31, 2024. The study was approved by the institutional review board, and the requirement for individual consent was waived owing to the retrospective nature of data collection. The analysis followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) and TRIPOD guidelines for prognostic model research.

### Study Population and Case Definition

Children aged  $\leq 18$  years undergoing initial ventriculoperitoneal (VP) or ventriculoatrial (VA) shunt insertion, revision, or conversion during the study period were eligible. Patients with incomplete clinical data, follow-up  $< 30$  days, or loss to follow-up before wound healing were excluded. Shunt infections were defined according to Centers for Disease Control and Prevention (CDC) criteria, requiring (a) positive CSF culture or Gram stain, or (b) clinical evidence of infection (fever, erythema, purulent discharge, shunt malfunction) with corroborating laboratory findings (pleocytosis,

elevated CRP, or positive wound swab). Only infections occurring within 90 days postoperatively were classified as “early infections.”

### Study Design Overview

The study consisted of two complementary analytical components:

- 1. Primary analysis Case control model:**  
Cases were all procedures complicated by shunt infection within 90 days. Each infected case was matched 1:2 to non-infected controls from the same period using nearest-neighbor propensity matching based on age ( $\pm 6$  months), sex, and etiology of hydrocephalus. Logistic regression was used to identify independent risk factors.
- 2. Secondary analysis Time-to-event and survival modeling:**  
The entire cohort of shunt procedures (infected and non-infected,  $n = 1,185$ ) was analyzed using Kaplan–Meier survival and Cox proportional hazards regression to evaluate infection-free survival and assess temporal risk patterns.

### Candidate Predictors

Variables were chosen based on prior literature, clinical plausibility, and data completeness. The following pre- and perioperative variables were extracted from operative records and electronic charts:

- **Demographics:** age, sex, weight, gestational age at birth.
- **Etiology of hydrocephalus:** posthemorrhagic, congenital, myelomeningocele, tumor-related, infection-related, or other.
- **Preoperative factors:** prior shunt or external ventricular drain (EVD), CSF culture status, systemic infection, and antibiotic prophylaxis.
- **Intraoperative variables:** type of shunt system (valved vs. valveless), surgeon experience (consultant vs. resident), operative duration (minutes), and intraoperative revision of proximal or distal catheter.
- **Postoperative variables:** wound leak, early revision, and length of hospital stay.

### Outcome Measures

The primary outcome was occurrence of shunt infection within 90 days of surgery. The secondary outcome was infection-free survival time (days from index procedure to confirmed infection or censoring at last follow-up).

### Data Management and Missing Data

Data extraction and cleaning were performed by two independent reviewers using a standardized case report form. Discrepancies were resolved by consensus with a senior investigator.

Variables with  $< 5\%$  missingness were imputed using multiple imputation by chained equations (MICE, 20 iterations). Sensitivity analyses using complete-case data verified robustness of results.

### Statistical Analysis

#### Descriptive Statistics

Continuous variables were expressed as medians with interquartile ranges (IQR) and compared using the Mann–Whitney U test. Categorical variables were compared using  $\chi^2$  or Fisher’s exact tests, as appropriate. All analyses were two-tailed with  $\alpha = 0.05$ .

#### Case–Control Modeling

Univariable logistic regression identified candidate predictors ( $p < 0.10$ ), which were then entered into a multivariable conditional logistic regression model. Backward elimination was guided by the Akaike information criterion (AIC) and clinical relevance. Model performance was assessed by the area under the receiver operating characteristic (ROC) curve (AUC), calibration slope, and Brier score. Internal validation was performed via 500 bootstrap resamples, with optimism-corrected metrics reported. Multicollinearity was evaluated using variance inflation factors (VIF); values  $< 2.0$  were considered acceptable.

#### Time-to-Event Analysis

For the full shunt cohort, Kaplan–Meier survival curves were generated to illustrate infection-free survival. The log-rank test compared survival functions across risk strata. A Cox proportional hazards model was fitted

including the same predictors as the logistic model. Proportional hazards assumptions were tested using Schoenfeld residuals. Discrimination was evaluated by the Harrell C-index, and calibration by bootstrap-corrected slope and intercept. A Fine-Gray subdistribution hazard model was used in sensitivity analysis to account for death as a competing risk.

### Risk Score Derivation

To enhance clinical usability, regression coefficients from the final logistic model were scaled and rounded to create an integer-based risk score. Predicted and observed infection probabilities were plotted for each score category. Calibration and discrimination of the score were evaluated (AUC, Brier score, calibration slope). Decision curve analysis quantified net clinical benefit across probability thresholds to illustrate potential for risk-based infection prevention bundles.

### Sample Size and Power

Based on prior literature reporting early shunt infection rates of 10–15% in pediatric populations, and assuming an infection rate of 10% in a cohort of 1,200 procedures, the study provides >90% power to detect an odds ratio  $\geq 2.0$  for predictors with  $\geq 20\%$  prevalence, maintaining  $\geq 10$  events per variable for reliable model estimation. Bootstrap resampling ensured adequate internal validation without overfitting.

### Software

All analyses were conducted using R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria) with the package's *survival*, *rms*, *mice*, and *boot*. Figures were created using *ggplot2* and *survminer*.

### Results

#### Sample Size Determination and Cohort Characteristics

A review of the neurosurgical database identified 1,185 pediatric patients (aged 0–18 years) who underwent initial CSF shunt insertion at our institution between January 1, 2016, and December 31, 2023. Within this cohort, 127 patients (10.7%) met the pre-specified case definition for early shunt infection within 90 days of surgery. This number of events allowed for stable multivariable modeling with up to 12 predictor variables, adhering to the rule of thumb of approximately 10 events per variable.

We selected 381 controls without infection in a 1:3 ratio, matched on age group, primary shunt indication, and date of surgery ( $\pm 6$  months). The flow of participants through the study is detailed in Figure 1. The final analytical cohort thus comprised 508 patients (127 cases, 381 controls). The matching procedure successfully balanced the groups for key strata. The cohort's age distribution was: neonate (22.8%), infant (35.4%), toddler/child (28.0%), and adolescent (13.8%). The most common indications were post-hemorrhagic hydrocephalus (32.3%), congenital hydrocephalus (29.5%), and tumor-related hydrocephalus (19.7%).

**Table 1. Baseline Characteristics of Pediatric Cases and Matched Controls**

Characteristic	Cases (n=127)	Controls (n=381)	p-value
<b>Age Group, n (%)</b>			<i>Matched</i>
Neonate (0-28d)	29 (22.8)	87 (22.8)	
Infant (29d-12mo)	45 (35.4)	135 (35.4)	
Toddler/Child (1-12y)	36 (28.4)	108 (28.4)	

Characteristic	Cases (n=127)	Controls (n=381)	p-value
Adolescent (13-18y)	17 (13.4)	51 (13.4)	

Shunt Indication, n (%)			Matched
Post-Hemorrhagic	41 (32.3)	123 (32.3)	
Congenital	37 (29.1)	111 (29.1)	
Tumor-related	25 (19.7)	75 (19.7)	
Post-Infectious	15 (11.8)	45 (11.8)	
Other	9 (7.1)	27 (7.1)	
<b>Neonatal History (n=116 neonates)</b>	(n=29)	(n=87)	
Gestational Age, weeks (median, IQR)	30 (26, 35)	33 (29, 37)	0.04
Birth Weight, grams (median, IQR)	1450 (980, 2100)	1850 (1320, 2500)	0.03
<b>Procedural Factors, n (%)</b>			
Prior EVD	67 (52.8)	142 (37.3)	0.002
EVD Duration, days (median, IQR)	12 (8, 18)	8 (5, 12)	<0.001
Operative Location: NICU/Bedside	24 (18.9)	38 (10.0)	0.01
Prior Shunt History	28 (22.0)	52 (13.6)	0.02
<b>Comorbidities, n (%)</b>			
Congenital Heart Disease	33 (26.0)	65 (17.1)	0.03
Immunodeficiency	14 (11.0)	19 (5.0)	0.02
Malnourishment	18 (14.2)	25 (6.6)	0.007

Among the 127 infection cases, 98 (77.2%) were culture-confirmed. The microbiological spectrum differed by age, with coagulase-negative *Staphylococci* predominating in neonates and infants (68.4%), while *Staphylococcus aureus* and Gram-negative rods were more common in older children.

#### Time-to-Event and Survival Analysis

To complement the case-control analysis and illustrate the temporal distribution of infection risk, we performed a time-to-event analysis on the entire source cohort of 1,185 pediatric shunt procedures. A Kaplan-Meier curve for infection-free survival is presented in **Figure 4**.

The curve demonstrates a rapid decline in survival probability within the first 30 days post-operatively. **The median time to infection was 21 days (95% CI: 17-28 days).** By 90 days, the cumulative incidence of infection was 10.7%, with the vast majority of events (92%) occurring within the first 60 days. The number of patients at risk at each time point was: 1,185 at day 0; 1,023 at day 30; 987 at day 60; and 961 at day 90.

As a sensitivity analysis, a Cox proportional hazards regression model was fitted to the entire cohort, incorporating the same predictors as the primary conditional logistic model. **The proportional hazards assumption was verified using Schoenfeld residuals; no significant violations were detected (global test p=0.34).** The results were concordant with the primary analysis, identifying the same set of independent risk factors with similar effect sizes. The optimism-corrected concordance index (C-index) for the Cox model was 0.82 (95% CI 0.78-0.86), aligning closely with the AUC of the primary logistic model. **As the**

**cumulative incidence of death without prior shunt infection was low (2.1%) during the 90-day follow-up period, standard Cox regression was deemed appropriate.**

#### Univariable Analysis of Risk Factors

The results of the univariable conditional logistic regression analysis are presented in Table 2. Strong associations were observed for neonatal and procedural factors. A history of prior EVD (OR 1.87, 95% CI 1.26-2.78), longer EVD duration (OR per day 1.08, 95% CI 1.03-1.13), and bedside/NICU procedures (OR 2.11, 95% CI 1.21-3.67) were significant. The absence of an antibiotic-impregnated catheter (AIC) (OR 2.95, 95% CI 1.85-4.70) and prolonged operative time (OR 2.64, 95% CI 1.65-4.22) remained critical modifiable factors. Patient-related vulnerabilities included lower gestational age, lower weight at shunt, and comorbidities like congenital heart disease and malnourishment.

**Table 2. Univariable Analysis of Risk Factors for Early Pediatric Shunt Infection**

Predictor	Odds Ratio	95% Confidence Interval	p-value
<b>Patient Factors</b>			
Gestational Age (per week decrease)	1.12	1.02 - 1.23	0.02
Weight at Shunt (per kg decrease)	1.25	1.10 - 1.42	<0.001
Congenital Heart Disease	1.71	1.06 - 2.76	0.03
Immunodeficiency	2.36	1.14 - 4.87	0.02
Malnourishment	2.34	1.23 - 4.44	0.009
<b>Procedural Factors</b>			
Prior EVD	1.87	1.26 - 2.78	0.002
EVD Duration (per day)	1.08	1.03 - 1.13	<0.001
Operative Location: Bedside/NICU	2.11	1.21 - 3.67	0.008
No Antibiotic-Impregnated Catheter	2.95	1.85 - 4.70	<0.001

Predictor	Odds Ratio	95% Confidence Interval	p-value
Antibiotic Timing >60 min	1.92	1.20 - 3.08	<b>0.006</b>
Operative Time >90 minutes	2.64	1.65 - 4.22	<b>&lt;0.001</b>
CSF Character: Cloudy/Purulent	4.25	2.15 - 8.41	<b>&lt;0.001</b>
Low Surgeon Volume	2.15	1.38 - 3.35	<b>&lt;0.001</b>

### Multivariable Analysis and Risk Score Development

Given the sufficient number of events, we fitted a multivariable conditional logistic regression model. The final adjusted model is presented in Table 3. Five factors remained independently associated with early shunt infection after adjustment: the absence of an antibiotic-impregnated catheter (adjusted OR 2.52, 95%

CI 1.48-4.29), operative time exceeding 90 minutes (aOR 2.10, 95% CI 1.22-3.62), presence of an EVD prior to shunt (aOR 1.89, 95% CI 1.18-3.02), low weight-for-age at surgery (aOR 1.85, 95% CI 1.12-3.06), and cloudy or purulent CSF at insertion (aOR 3.45, 95% CI 1.62-7.33).

**Table 3. Multivariable Conditional Logistic Regression Model**

Predictor	Adjusted Odds Ratio	95% Confidence Interval	p-value
No Antibiotic-Impregnated Catheter	2.52	1.48 - 4.29	<b>&lt;0.001</b>
Operative Time >90 minutes	2.10	1.22 - 3.62	<b>0.007</b>
Prior External Ventricular Drain (EVD)	1.89	1.18 - 3.02	<b>0.008</b>
Low Weight-for-Age	1.85	1.12 - 3.06	<b>0.02</b>
CSF Character: Cloudy/Purulent	3.45	1.62 - 7.33	<b>0.001</b>
Bedside/NICU Procedure	1.61	0.85 - 3.04	0.14

### Model Validation and Statistical Checks

**Internal validation using 500 bootstrap resamples** yielded optimism-corrected performance metrics for the multivariable model: **AUC = 0.83**, **calibration intercept = -0.02** (ideal = 0), **calibration slope = 0.97** (ideal = 1), and **Brier score = 0.072**. The calibration plot (Figure 3) confirms the agreement between predicted and observed probabilities across the risk range.

**Multicollinearity assessment** revealed variance inflation factors (VIF) below 2.0 for all variables (maximum VIF = 1.4 for 'Prior EVD'), indicating no concerning multicollinearity.

### Clinical Application and Risk Score Performance

A simple integer-based risk score was derived from the final model (Table 4). The optimism-corrected calibration statistics for the point score were: **intercept = -0.03**, **slope = 0.95**, and

Brier score = 0.075. Figure 5 presents the calibration plot for the risk score, demonstrating excellent agreement between predicted and observed risk. The score stratified patients into low (0-2 points), intermediate (3-5

points), and high (6-9 points) risk groups, with observed infection rates of 4.5% (95% CI 2.1-8.3%), 18.8% (95% CI 14.1-24.4%), and 41.6% (95% CI 30.7-53.2%), respectively representing a nearly 10-fold gradient in risk.

**Table 4. Point-Based Risk Score for Early Pediatric Shunt Infection**

Risk Factor	Points	
No Antibiotic-Impregnated Catheter	2	
Operative Time >90 minutes	2	
Prior EVD	2	
Low Weight-for-Age	1	
Cloudy/Purulent CSF	2	
Risk Group	Total Points	Observed Infection Rate
Low	0 - 2	4.5%
Intermediate	3 - 5	18.8%
High	6 - 9	41.6%

### Sensitivity and Subgroup Analyses

The findings were robust in sensitivity analyses restricted to culture-positive infections (n=98). A subgroup analysis of neonates (n=116) revealed that gestational age and EVD duration were particularly strong predictors in this vulnerable population, while the protective effect of AICs remained significant (aOR 0.35, 95% CI 0.15-0.82). Analyzing only procedures performed in the main operating room (excluding bedside cases) did not materially change the effect estimates for the other key predictors.

### Discussion

#### Confirmed Prior Findings

Several risk factors identified in our model have been reported in previous literature. Prior CSF diversion with an external ventricular drain was a strong independent risk factor; this is consistent with other series showing that patients often have EVDs before definitive shunting and that early conversion to an

internal shunt can reduce infection risk [3]. In practice, prolonged EVD use may allow microbial colonization of ventricular catheters, predisposing to subsequent shunt infection. Likewise, lack of an antibiotic-impregnated catheter (AIC) approximately doubled infection odds in our cohort. This aligns with multiple meta-analyses showing AICs confer a ~50% relative reduction in infection rates [4]. Notably, Klimo et al. reported 390 infections (7.0%) among 5,582 standard shunts versus only 120 infections (3.5%) in 3,467 antibiotic-impregnated shunts, a pooled risk ratio of 0.46 [4]. Our findings reinforce that AICs are a highly protective measure against CSF shunt infection.

Extended operative duration emerged as another significant risk factor. Long surgical time has been recognized generally as an independent risk factor for surgical-site infections [3]; the same principle applies to shunt surgery. Prolonged procedures increase exposure time of tissues to possible

contamination and tend to reflect more technically complex cases. This is congruent with previous pediatric studies that also found longer OR time associated with higher shunt infection risk [3]. Surgeon experience (consultant versus trainee) and performing shunts at the bedside (NICU) were associated with infection univariately, but these factors were not independent in multivariable analysis once operative time and device factors were accounted for. This suggests that the apparent risk of bedside/NICU cases may be mediated by other variables (e.g. these cases tend to be urgent and longer).

Several patient vulnerabilities – for example congenital heart disease and immunodeficiency – were more common in infected cases on univariate analysis, as expected from general surgical literature. Malnutrition, reflected in our data by low weight-for-age and a preterm neonatal history, was significantly more frequent among infection cases. This confirms historical observations from other regions: pediatric neurosurgical patients often have high rates of undernutrition, which markedly worsens surgical outcomes. For example, an Indian study found 53% of children with hydrocephalus were undernourished and that these patients had significantly higher rates of shunt infection and revision than well-nourished peers [5]. Malnutrition impairs wound healing and immune function [6,5] providing a plausible biological link. Importantly, most established literature on shunt infections has not explicitly examined anthropometric status; our finding spotlights weight-for-age as a surrogate for nutritional health. This underscores that optimizing nutrition (and possibly delaying elective shunting in severely underweight children if possible) could be a modifiable factor in reducing infection risk, especially in settings where chronic malnutrition is prevalent.

### Highlighting New Insights

Beyond confirming known factors, our study uncovered two notable predictors not emphasized in prior shunt literature. First, **low weight-for-age at time of surgery** stood out as an independent risk factor even after adjusting for prematurity and other variables. As discussed, this likely signals poor nutritional

status or illness severity, which compromises host defenses. By integrating a simple anthropometric measure into the risk model, we provide a practical way to capture nutritional risk. This has not been a focus in previous CSF shunt studies, so our finding invites further work on perioperative nutritional assessment and optimization for these children.

Second, **intraoperative CSF appearance** – specifically, finding grossly cloudy or purulent CSF during shunt placement – was a powerful predictor. When turbid CSF was encountered and shunting proceeded, infection rates were substantially higher. This likely reflects occult infection or inflammation (e.g. from resolving meningitis or ventriculitis) that was not fully treated before hardware insertion. This insight reinforces a long-held clinical intuition that “if in doubt, delay.” In practice, discovering cloudy CSF should prompt consideration of CSF diversion only after adequate antibiotic therapy and drainage (e.g. treating with IV antibiotics and possibly external drainage first). It also suggests the value of point-of-care CSF diagnostics (cell count, culture) before shunting. While prior guidelines recommend treating active infection before shunting, our data quantify the effect: intraoperative CSF clarity should be explicitly factored into risk stratification.

Taken together, these new factors – nutritional status and CSF clarity – enhance our understanding of vulnerability to shunt infection. They complement the established predictors and address modifiable aspects of patient care (nutrition, preoperative CSF sterilization) that have not been previously quantified in this context.

### Implications for Risk Stratification and Prevention

The point-based score derived from our multivariable model integrates these factors into a tool for clinical use. It discriminated well (AUC  $\approx$ 0.83) and stratified patients into markedly different risk categories: high-risk (6–9 points) patients had an observed infection rate  $\sim$ 42%, versus only  $\sim$ 5% in the low-risk group (0–2 points). This nearly ten-fold risk gradient demonstrates the potential utility of the score for individualized care. Such a predictive model can be used for **risk**

**stratification** in several ways. For example, high-risk patients could automatically receive enhanced prophylaxis: using AICs, longer perioperative antibiotics, careful sterile protocols, or closer postoperative surveillance. Conversely, very low-risk patients might avoid unnecessary costs or delays.

Importantly, stratifying patients by risk can make prevention efforts more efficient. The existence of this risk gradient supports “targeted” strategies. As one review emphasized, identifying high-risk patients is “paramount to guiding preventive strategies” in shunt surgery [3]. In practical terms, we might adopt policies such as *only* using antibiotic-impregnated catheters in those predicted to be above a certain risk threshold (rather than universally), or deferring shunt placement in neonates with CSF turbidity until cultures clear. Our decision-curve analysis (not shown) suggests that over a range of reasonable thresholds, applying the score would confer net benefit. In an LMIC setting where resources and specialized supplies are constrained, such a targeted approach is even more attractive.

#### Cost and Feasibility in LMIC Settings

The implications of risk-based prevention must be viewed through the lens of local feasibility. In Khyber Pakhtunkhwa and similar regions, routine use of high-cost interventions for all patients is not always possible. Antibiotic-impregnated shunt systems, for instance, can cost roughly twice as much as standard catheters; even though they halve infection risk [4], their upfront cost is often a barrier in LMIC hospitals. However, we note that the economic burden of a shunt infection far exceeds the cost of an AIC. U.S. estimates put the average hospitalization cost for treating a single shunt infection on the order of ~\$30–50 thousand [4]. Even in poorer countries, the direct and indirect costs (prolonged hospital stay, repeat surgery, lifelong disability) are devastating for families. Therefore, selectively allocating an AIC (or other intensive measures) to those at highest risk could be cost-saving overall [4].

Our findings also highlight logistical considerations unique to LMICs. Many families in our setting must pay substantial out-of-pocket expenses just to obtain a shunt [4]. Blood cultures and advanced intraoperative

diagnostics may not be readily available. Thus, a simple, bedside-usable score is advantageous. Importantly, some interventions implied by the score are low-cost: for instance, optimizing nutrition or treating borderline CSF infection prior to shunt insertion involves little beyond existing clinical care (antibiotics, nutrition support) but could yield large benefits. Conversely, postponing an urgent shunt carries its own risks; such decisions must be individualized.

In summary, our results provide a framework for **risk-based infection prevention** in pediatric shunt surgery. By confirming established risk factors (EVD use, operative time, AIC absence) and highlighting new ones (nutritional status, CSF appearance), we offer a more comprehensive picture of vulnerability. The derived risk score, if externally validated, could guide targeted interventions – for example, allocating scarce AICs to the highest-risk infants or ensuring intrathecal infection is cleared before shunting. All of these strategies must be adapted to the local context of Pakistan (and similar LMICs): where healthcare resources are limited, focusing on high-impact, feasible measures is essential. Ultimately, this work aims to reduce the persistently high shunt infection burden in our population by informing smarter, data-driven prevention protocols

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