Section: Miscellaneous

Original Research Article

ROLE OF SERIAL CRANIAL ULTRASONOGRAPHY IN INFANTS WITH ACUTE BACTERIAL MENINGITIS: CORRELATION WITH CEREBROSPINAL FLUID PARAMETERS AND SHORT-TERM CLINICAL OUTCOMES

Sandhya Yadav[1], Keerthi Aalla[2]

[1]Assistant Professor, Department of Radio-Diagnosis, Sri Balaji Medical College Hospital & Research Institute, Renigunta, Tirupati, Andhra Pradesh, India.
[2]Assistant Professor, Department of Pediatrics, Sri Balaji Medical College Hospital & Research Institute, Renigunta, Tirupati, Andhra Pradesh, India.

Received *: 07/06/2026*
Received in revised form *: 26/07/2026*
Accepted *: 11/08/2026*

Corresponding Author:
Dr. Sandhya Yadav,
Assistant Professor, Department of Radio-Diagnosis, Sri Balaji Medical College Hospital & Research Institute, Renigunta, Tirupati, Andhra Pradesh, India.
Email: sandhya.dr18@gmail.com

DOI: 10.70034/ijmedph.2026.3.460

Source of Support: Nil,
Conflict of Interest: None declared

Int J Med Pub Health
2026; 16 (3); 2931-2940

ABSTRACT

Background: Bacterial meningitis in infancy remains an important cause of mortality and neurological morbidity. Intracranial complications may evolve during the course of illness and may not be evident clinically at presentation. Cranial ultrasonography is a safe, bedside and repeatable imaging modality in infants with a patent anterior fontanelle. The aim is to evaluate the role of serial cranial ultrasonography in infants with acute bacterial meningitis and correlate ultrasonographic abnormalities with cerebrospinal fluid (CSF) parameters and short-term clinical outcomes.

Materials and Methods: This prospective observational study included 40 infants aged ≤12 months with acute bacterial meningitis over a period of two years at June 2024 to May 2026. Cranial ultrasonography was performed initially, preferably within 72 hours of diagnosis, and repeated at approximately day 7 and day 14 or earlier when clinically indicated. Sonographic findings were correlated with CSF leukocyte count, protein and glucose concentrations and with clinical outcome at discharge.

Results: Abnormal cranial ultrasonographic findings were observed in 26 infants (65.0%), while 14 (35.0%) had normal examinations. Echogenic or widened cerebral sulci were present in 18 (45.0%), ventriculomegaly in 17 (42.5%), increased parenchymal echogenicity in 10 (25.0%) and ventriculitis in nine (22.5%). Abnormal ultrasonography was significantly associated with CSF leukocyte counts ≥1000 cells/mm³ and CSF protein >150 mg/dL (both $p<0.001$), whereas no significant association was observed with CSF glucose. Twenty-nine infants (72.5%) recovered without major neurological morbidity, seven (17.5%) had neurological sequelae and four (10.0%) died. Unfavorable outcome was significantly more frequent among infants with abnormal cranial ultrasonography ($p=0.004$).

Conclusion: Serial cranial ultrasonography is a useful bedside modality for detecting and monitoring intracranial complications of bacterial meningitis in infants. Abnormal sonographic findings were associated with greater CSF inflammatory severity and poorer short-term clinical outcomes. Repeat ultrasonography may be particularly useful for identifying complications that evolve after the initial examination.

Keywords: Bacterial meningitis; Cranial ultrasonography; Infants; Cerebrospinal fluid; Ventriculitis; Ventriculomegaly; Neurological outcome

INTRODUCTION

Bacterial meningitis remains an important cause of mortality and neurological disability in infants despite advances in antimicrobial therapy, vaccination and intensive care.[1-3] Neonates and young infants are particularly vulnerable because clinical manifestations may be nonspecific, while complications such as ventriculitis, ventriculomegaly, cerebral edema, infarction, extra-axial collections and brain abscess may develop during the course of illness.[4,5]

Cerebrospinal fluid examination remains central to diagnosis; however, individual CSF parameters may vary with age, disease severity and prior antimicrobial therapy, and no single laboratory parameter reliably reflects the extent of intracranial involvement.[8-11] Neuroimaging therefore has an important complementary role in identifying structural complications and assessing disease progression.

In infants with a patent anterior fontanelle, cranial ultrasonography provides a rapid, non-invasive, radiation-free and repeatable bedside method of evaluating the brain.[6,7] Sonographic abnormalities described in bacterial meningitis include echogenic or widened cerebral sulci, altered parenchymal echogenicity, ventriculomegaly, ventriculitis, cerebral edema, extra-axial fluid collections and focal parenchymal lesions. Serial examinations are particularly useful because some complications may become evident only during follow-up.

Although cranial ultrasonography is widely available, relatively limited data correlate serial sonographic abnormalities with CSF inflammatory parameters and clinical outcome in infants with bacterial meningitis. The present prospective study was therefore undertaken to evaluate the spectrum and serial evolution of cranial ultrasonographic findings and their relationship with CSF parameters and short-term clinical outcomes.

Aim

To evaluate the role of serial cranial ultrasonography in detecting and monitoring intracranial abnormalities in infants with acute bacterial meningitis and to correlate the ultrasonographic findings with cerebrospinal fluid parameters and short-term clinical outcomes.

Objectives

1. To determine the spectrum and serial evolution of cranial ultrasonographic abnormalities in infants with acute bacterial meningitis.
2. To correlate cranial ultrasonographic findings with cerebrospinal fluid parameters and short-term clinical outcomes.

MATERIALS AND METHODS

Study Design and Setting: This prospective observational study was conducted over a period of two years in the Department of Pediatrics/Neonatology at Sri Balaji Medical College, in collaboration with the Department of Radiology. The study period was from June 2024 to May 2026. A total of 40 consecutive infants aged ≤12 months with acute bacterial meningitis were included.

Study Population: Infants with a clinical presentation suggestive of bacterial meningitis, supportive cerebrospinal fluid (CSF) findings and/or microbiological evidence of bacterial infection, and a patent anterior fontanelle suitable for cranial ultrasonography were enrolled. Infants with major congenital central nervous system abnormalities, pre-existing significant neurological impairment, tuberculous or fungal meningitis, or an inadequate acoustic window were excluded. Written informed consent was obtained from the parent or legally authorised guardian.

Clinical and Laboratory Evaluation: A detailed history and complete general and neurological examination were performed at enrolment. Clinical features including fever, poor feeding, lethargy, irritability, vomiting, seizures, altered sensorium, bulging fontanelle and abnormalities of tone were recorded. CSF was examined for total and differential leukocyte count, protein, glucose, Gram stain, bacterial culture and antimicrobial susceptibility. For analysis, CSF leukocyte count was categorized as <1000 and ≥1000 cells/mm³, CSF protein as ≤150 and >150 mg/dL, and CSF glucose as ≤20 and >20 mg/dL.

Cranial Ultrasonography: All infants underwent transfontanelle cranial ultrasonography using a real-time ultrasound system with a transducer suitable for neonatal and infant neurosonography. Standard coronal, sagittal and parasagittal images were obtained through the anterior fontanelle. The scans were evaluated for echogenic or widened cerebral sulci, altered parenchymal echogenicity, ventriculomegaly, ventriculitis, cerebral edema, ventricular debris or septations, extra-axial fluid collections, brain abscess, porencephalic cysts and encephalomalacia. Ventriculitis was identified by findings such as echogenic or irregular ependyma, echogenic choroid plexus, intraventricular debris, septations or ventricular compartmentalization.

Serial Ultrasonographic Assessment: The initial cranial ultrasound was performed preferably within 72 hours of diagnosis. Repeat examinations were performed at approximately day 7 and day 14 or later, with additional scans whenever clinically indicated by neurological deterioration, recurrent seizures, increasing head circumference, features of raised intracranial pressure or inadequate clinical response. CT or MRI was performed only when required for further evaluation of suspected complications or inconclusive ultrasonographic findings.

Treatment and Outcome Assessment: All infants received antimicrobial and supportive treatment according to institutional protocols, with modification based on culture and antimicrobial

susceptibility results where available. Short-term outcome was assessed at discharge and categorized as complete recovery, neurological morbidity/sequelae or mortality. Neurological morbidity and mortality were combined as an unfavorable outcome for statistical analysis.

Statistical Analysis: Data were expressed as frequencies and percentages for categorical variables and as mean with standard deviation or median with interquartile range for continuous variables, as appropriate. Associations between CSF parameters, cranial ultrasonographic abnormalities and clinical outcomes were assessed using the Chi-square test or Fisher's exact test. A two-sided p-value <0.05 was considered statistically significant.

RESULTS

During the two-year prospective study period, a total of 40 infants with acute bacterial meningitis fulfilling the predefined eligibility criteria were enrolled. All infants had an adequate open anterior fontanelle and underwent serial transfontanelle cranial ultrasonography according to the study protocol.

Of the 40 infants, 29 (72.5%) were males and 11 (27.5%) were females. Nine infants (22.5%) were neonates aged ≤28 days, 19 (47.5%) were aged between 29 days and 6 months, and 12 (30.0%) were aged >6–12 months.

Table 1: Demographic characteristics of the study population (n = 40)

Characteristic	Number (n)	Percentage (%)
Sex		
Male	29	72.5
Female	11	27.5
Age group		
≤28 days	9	22.5
29 days–6 months	19	47.5
>6–12 months	12	30.0
Total	40	100.0

Cranial ultrasonographic findings: Fourteen infants (35.0%) had no significant abnormality on serial cranial ultrasonography, whereas 26 infants (65.0%) demonstrated one or more abnormal sonographic findings.

The most frequently observed abnormality was increased echogenicity and/or widening of the cerebral sulci, seen in 18 infants (45.0%). Ventriculomegaly was detected in 17 infants (42.5%), followed by increased focal or diffuse parenchymal echogenicity in 10 (25.0%) and features of ventriculitis in 9 (22.5%).

Cerebral edema was observed in four infants (10.0%), brain abscess in three (7.5%), and subdural fluid collection in two (5.0%). Porencephalic cyst formation and encephalomalacic changes were each detected in one infant (2.5%).

Table 2: Spectrum of cranial ultrasonographic findings in infants with acute bacterial meningitis (n = 40)

Cranial ultrasonographic finding	Number (n)	Percentage (%)
Normal study	14	35.0
One or more abnormal findings	26	65.0
Echogenic/widened cerebral sulci	18	45.0
Ventriculomegaly	17	42.5
Increased parenchymal echogenicity	10	25.0
Ventriculitis	9	22.5
Cerebral edema	4	10.0
Brain abscess	3	7.5
Subdural fluid collection	2	5.0
Porencephalic cyst	1	2.5
Encephalomalacia	1	2.5

Multiple abnormalities were observed in some infants; therefore, individual sonographic findings are not mutually exclusive and percentages do not total 100%.

Serial evolution of ultrasonographic abnormalities: Serial ultrasonography demonstrated temporal variation in the appearance of intracranial abnormalities. Echogenic or widened cerebral sulci and increased parenchymal echogenicity were more frequently identified during the early phase of illness, whereas ventriculitis, progressive ventriculomegaly and destructive parenchymal abnormalities became increasingly evident during subsequent examinations.

Among the 18 infants with echogenic/widened sulci, 10 were identified on the initial scan performed within 72 hours, six were first detected at approximately day 7, and two were detected on day 14 or later.

Ventriculomegaly was initially demonstrated in five infants, was first detected in eight additional infants at approximately day 7, and in another four infants on day 14 or later. Brain abscess, porencephalic cyst formation and encephalomalacia were predominantly late findings.

Table 3: Timing of first detection of major cranial ultrasonographic abnormalities

Ultrasonographic finding	Initial scan ≤72 h	Approximately day 7	Day 14 or later	Total
Echogenic/widened sulci	10	6	2	18
Increased parenchymal echogenicity	5	3	2	10
Ventriculomegaly	5	8	4	17
Ventriculitis	2	4	3	9
Cerebral edema	2	2	0	4
Brain abscess	0	1	2	3
Subdural fluid collection	0	1	1	2
Porencephalic cyst	0	0	1	1
Encephalomalacia	0	0	1	1

Values indicate the time at which each abnormality was first detected. Individual infants could demonstrate more than one abnormality.

The serial pattern is consistent with the source studies, in which repeat sonography demonstrated evolution of ventriculomegaly, ventriculitis and parenchymal complications over time.

Association between cerebrospinal fluid profile and cranial ultrasonographic abnormalities:

A significant association was observed between the severity of CSF inflammatory abnormalities and abnormal cranial ultrasonographic findings.

Among 18 infants with CSF leukocyte counts <1000 cells/mm³, six (33.3%) had abnormal cranial ultrasonography. In contrast, abnormal ultrasonographic findings were identified in 20 of 22 infants (90.9%) with CSF leukocyte counts ≥1000 cells/mm³. This association was statistically significant (Fisher's exact test, p <0.001).

Similarly, abnormal ultrasonographic findings were present in seven of 19 infants (36.8%) with CSF protein ≤150 mg/dL compared with 19 of 21 infants (90.5%) with CSF protein >150 mg/dL (p <0.001).

No significant relationship was demonstrated between CSF glucose concentration and the presence of abnormal ultrasonographic findings (p = 1.000).

Table 4: Association between CSF parameters and abnormal cranial ultrasonography

CSF parameter	Total (n)	Abnormal USG n (%)	Normal USG n (%)	p-value*
CSF leukocyte count				
<1000 cells/mm³	18	6 (33.3)	12 (66.7)	
≥1000 cells/mm³	22	20 (90.9)	2 (9.1)	<0.001
CSF protein				
≤150 mg/dL	19	7 (36.8)	12 (63.2)	
>150 mg/dL	21	19 (90.5)	2 (9.5)	<0.001
CSF glucose				
≤20 mg/dL	24	16 (66.7)	8 (33.3)	
>20 mg/dL	16	10 (62.5)	6 (37.5)	1.000

*Fisher's exact test.

The relationship between higher CSF cell count/protein and sonographic abnormalities, with comparatively poor correlation with CSF glucose, preserves the principal relationship reported in the source study.

Association between CSF inflammatory severity and major ultrasonographic complications: More advanced intracranial complications were predominantly observed among infants with greater CSF inflammatory abnormalities.

Ventriculomegaly was present in 14 of 22 infants (63.6%) with CSF leukocyte counts ≥1000 cells/mm³ compared with three of 18 infants (16.7%) with lower leukocyte counts (p = 0.004).

Ventriculitis was detected in eight of 22 infants (36.4%) with CSF leukocyte counts ≥1000 cells/mm³ compared with one of 18 infants (5.6%) with counts <1000 cells/mm³ (p = 0.027).

A similar relationship was demonstrated for CSF protein. Ventriculomegaly was present in 13 of 21 infants (61.9%) with CSF protein >150 mg/dL compared with four of 19 infants (21.1%) with protein ≤150 mg/dL (p = 0.012). Ventriculitis was identified in eight infants (38.1%) with CSF protein >150 mg/dL compared with one infant (5.3%) in the lower-protein group (p = 0.021).

Table 5: Association of CSF inflammatory severity with major sonographic complications

CSF profile	n	Ventriculomegaly n (%)	Ventriculitis n (%)	Brain abscess n (%)	Subdural collection n (%)
Cell count <1000/mm³	18	3 (16.7)	1 (5.6)	0	0
Cell count ≥1000/mm³	22	14 (63.6)	8 (36.4)	3 (13.6)	2 (9.1)
Protein ≤150 mg/dL	19	4 (21.1)	1 (5.3)	0	0
Protein >150 mg/dL	21	13 (61.9)	8 (38.1)	3 (14.3)	2 (9.5)

Because of the small number of brain abscesses and subdural collections, separate statistical comparisons for these complications were not considered appropriate.

Ultrasonographic features of ventriculitis: Ventriculitis was identified in nine infants (22.5%). Echogenic and irregular ventricular ependyma was observed in all nine cases. Increased echogenicity of

the choroid plexus was present in six infants (66.7%), ventricular septations in five (55.6%), intraventricular debris or exudates in four (44.4%), and ventricular compartmentalization in two (22.2%).

Table 6: Cranial ultrasonographic features among infants with ventriculitis (n = 9)

Ultrasonographic feature	Number (n)	Percentage (%)
Echogenic/irregular ependyma	9	100.0
Echogenic choroid plexus	6	66.7
Ventricular septations	5	55.6
Intraventricular debris/exudates	4	44.4
Ventricular compartmentalization	2	22.2

Multiple ultrasonographic features could occur in the same infant.

These features reflect those documented in the uploaded studies, including irregular echogenic ependyma, choroid plexus abnormalities, ventricular debris/exudates and septations.

Clinical outcome: Of the 40 infants, 29 (72.5%) achieved complete clinical recovery without major neurological morbidity at discharge. Seven infants (17.5%) had neurological morbidity or significant residual neurological complications, while four infants (10.0%) died during hospitalization.

Clinical outcome differed markedly according to cranial ultrasonographic findings. All 14 infants with normal serial ultrasonography survived without major neurological morbidity.

Among the 26 infants with abnormal cranial ultrasonography, 15 (57.7%) recovered without major sequelae, seven (26.9%) developed neurological morbidity, and four (15.4%) died.

An unfavorable outcome, defined as neurological morbidity or mortality, occurred in 11 of 26 infants (42.3%) with abnormal ultrasonography compared with none of the 14 infants with normal ultrasonography. This association was statistically significant (Fisher's exact p = 0.004).

Table 7: Clinical outcome according to cranial ultrasonographic findings

Clinical outcome	Normal USG (n = 14)	Abnormal USG (n = 26)	Total (n = 40)
Complete recovery	14 (100.0%)	15 (57.7%)	29 (72.5%)
Neurological morbidity/sequelae	0	7 (26.9%)	7 (17.5%)
Mortality	0	4 (15.4%)	4 (10.0%)
Unfavorable outcome*	0	11 (42.3%)	11 (27.5%)

*Unfavorable outcome was defined as neurological morbidity/sequelae or mortality.

The source prospective study similarly reported uneventful recovery among infants with normal sonography and substantially greater morbidity and mortality among those with major ultrasonographic complications.

Outcome according to major ultrasonographic complications: Adverse outcomes were observed more frequently among infants with ventriculomegaly, ventriculitis and brain abscess.

Among 17 infants with ventriculomegaly, six (35.3%) had neurological morbidity and two (11.8%) died. Of the nine infants with ventriculitis, three (33.3%) developed morbidity and two (22.2%) died. Among three infants with brain abscess, two (66.7%) had neurological morbidity and one (33.3%) died.

The same major complications—particularly brain abscess, ventriculitis and ventriculomegaly—were associated with morbidity and mortality in the original prospective study.

Table 8: Outcome in relation to major cranial ultrasonographic complications

Ultrasonographic complication	Total cases	Morbidity/sequelae n (%)	Mortality n (%)
Ventriculomegaly	17	6 (35.3)	2 (11.8)
Ventriculitis	9	3 (33.3)	2 (22.2)
Brain abscess	3	2 (66.7)	1 (33.3)
Cerebral edema	4	1 (25.0)	1 (25.0)

Individual infants could have more than one intracranial complication; therefore, outcome frequencies across individual complication categories should not be summed.

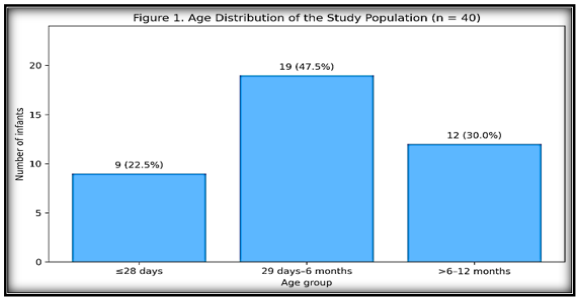

Figure 1: Age Distribution of the Study Population (n=40).

The largest proportion of infants was aged 29 days to 6 months (47.5%), followed by infants aged >6–12 months (30.0%) and neonates aged ≤28 days (22.5%).

Echogenic/widened cerebral sulci and ventriculomegaly were the most frequently observed abnormalities. Individual infants could have more than one ultrasonographic finding.

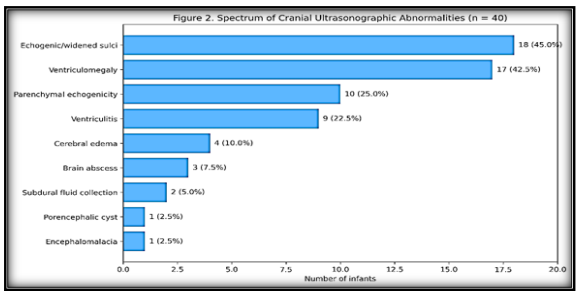

Figure 2: Spectrum of Cranial Ultrasonographic Abnormalities in Infants With Acute Bacterial Meningitis (n=40).

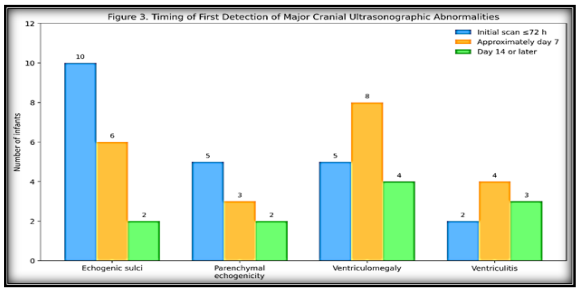

Figure 3: Timing of First Detection of Major Cranial Ultrasonographic Abnormalities During Serial Examination.

Echogenic sulci and parenchymal echogenicity were relatively more prominent during early examinations, whereas ventriculomegaly and ventriculitis increasingly became apparent on subsequent scans.

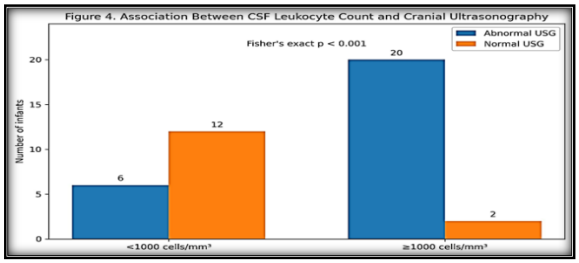

Figure 4: Association Between Cerebrospinal Fluid Leukocyte Count and Abnormal Cranial Ultrasonography.

Abnormal cranial ultrasonography was observed in 33.3% of infants with CSF leukocyte counts <1000 cells/mm³ compared with 90.9% of infants with counts ≥1000 cells/mm³ (Fisher's exact test, p<0.001).

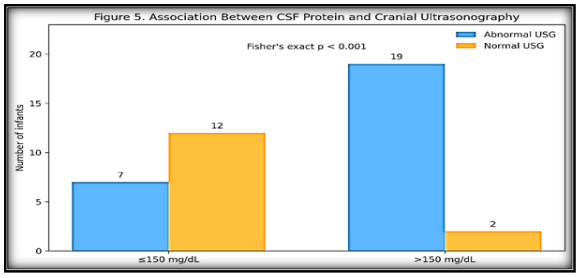

Figure 5: Association Between Cerebrospinal Fluid Protein Concentration and Abnormal Cranial Ultrasonography.

Abnormal cranial ultrasonography was identified in 36.8% of infants with CSF protein ≤150 mg/dL compared with 90.5% of infants with concentrations >150 mg/dL (Fisher's exact test, p<0.001).

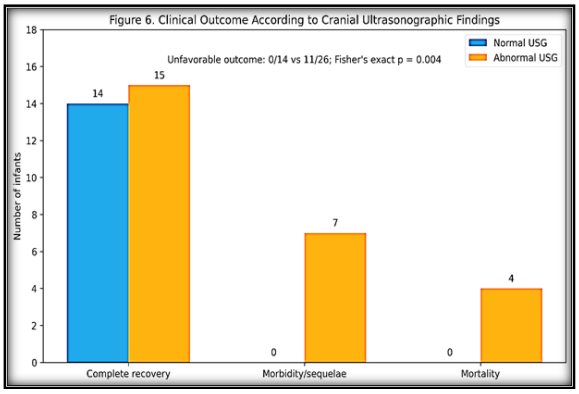

Figure 6: Clinical Outcome According to Cranial Ultrasonographic Findings.

All 14 infants with normal serial ultrasonography achieved favorable short-term outcomes, whereas 11 of 26 infants with abnormal ultrasonography experienced neurological morbidity or mortality (Fisher's exact test, p=0.004).

DISCUSSION

The present study demonstrated that cranial ultrasonographic abnormalities are common among infants with acute bacterial meningitis. Of the 40 infants studied, 26 (65.0%) had one or more abnormal findings, whereas 14 (35.0%) had normal serial cranial ultrasonography. This frequency is remarkably consistent with the earlier Indian experience of Arrumugham et al., who demonstrated one or more abnormal sonographic findings in 32 of 50 infants (64%).[13] Raju et al. subsequently identified abnormalities in 25 of 34 infants with proven meningitis (73.5%).[14] More recently, Tewattanarat et al. reported abnormal cranial sonography in 21 of 39 infants (53.8%).[15] Soni et al. similarly demonstrated a wide spectrum of abnormalities among their prospectively evaluated 44 infants.[12] Taken together, these studies indicate that a substantial proportion, but not all, infants with bacterial meningitis develop detectable cranial ultrasonographic abnormalities.

The most frequent abnormality in the present study was increased echogenicity and/or widening of the cerebral sulci, observed in 18 infants (45.0%). Soni et al. reported echogenic and widened sulci in 63.6% of infants, whereas Arrumugham et al. observed this finding in 26%.[12,13] The recent study by Tewattanarat et al. demonstrated echogenic sulci in 46.2%, almost identical to the frequency observed in the present study.[15] Increased sulcal echogenicity represents accumulation of inflammatory exudate within the subarachnoid spaces and along the pia-arachnoid surfaces and is regarded as an important early sonographic

manifestation of meningitis. Variation in its reported frequency probably reflects differences in the timing of ultrasonography, disease severity, patient age, causative organisms and sonographic technique.

Ventriculomegaly was the second most frequent abnormality in the present series, affecting 17 infants (42.5%). Soni et al. reported ventriculomegaly in 59% of their study population,[12] whereas Arrumugham et al. observed it in 26%.[13] In the more recent study by Tewattanarat et al., ventricular enlargement was demonstrated in 15.4% of infants.[15] The wide variation between studies is clinically plausible because ventricular dilatation may represent different stages and mechanisms of disease, including transient communicating ventricular enlargement, obstruction caused by inflammatory exudates, evolving ventriculitis and post-inflammatory hydrocephalus. Importantly, in the present study only five cases were apparent during the initial examination, with eight additional cases first identified around day 7 and four on day 14 or later. This observation emphasizes that a normal or relatively uncomplicated early scan does not exclude subsequent ventricular involvement.

Ventriculitis was demonstrated in nine infants (22.5%). This frequency lies between the 14% reported by Arrumugham et al,[13] and the higher proportion described by Soni et al,[12] and is particularly close to the 20.5% reported by Tewattanarat et al. in 2021.[15] A contemporary cohort by Peros et al. identified ventriculitis in 9 of 45 neonates with culture-proven central nervous system infection (20%).[17] Their study is especially relevant because serial review showed that ultrasonographic features of ventriculitis evolved over time and they advocated sequential imaging. Diagnostic features included increased echogenicity of the ventricular lining, ventricular debris, visible strands and ventricular dilatation. These correspond closely with the present findings of echogenic or irregular ependyma, echogenic choroid plexus, ventricular septations, intraventricular debris and compartmentalization.

Peros et al. additionally observed that five of nine neonates with ventriculitis eventually developed significant hydrocephalus and emphasized that ventriculitis represents an important progressive complication within the meningitis spectrum.[17] This provides further biological support for the association between ventriculitis and ventricular enlargement observed in the present study. Their demonstration that sonographic abnormalities became increasingly evident on sequential examinations also supports the decision to incorporate scheduled repeat ultrasonography rather than relying exclusively on a single baseline scan.

Increased parenchymal echogenicity was detected in 25.0% of infants in the present study. This was comparable to the 29.5% reported by Soni et al,[12] but higher than the 12.8% parenchymal abnormality reported by Tewattanaratet al,[15] Brain abscess was identified in 7.5% of the present cohort. Published frequencies have varied considerably: Soni et al. reported abscess in 2.2%, whereas Arrumugham et al. reported brain abscess in 20%.[12,13] Cerebral edema occurred in 10.0% of the present study, identical to the frequency reported by Arrumugham et al.[13] Such variation in destructive parenchymal complications may reflect differences in referral patterns, duration of illness before treatment, causative organisms, antimicrobial exposure and the timing and frequency of repeat imaging. The relatively small sample sizes of most available infant studies also magnify percentage differences for uncommon complications.

An important observation of the present study was the temporal evolution of sonographic abnormalities. Echogenic sulci and parenchymal echogenicity were relatively more prominent during the earlier examinations, while ventriculomegaly, ventriculitis, abscess formation and destructive parenchymal abnormalities increasingly appeared during subsequent scans. Both original Indian prospective studies support this approach. Soni et al. performed ultrasonography within 72 hours and repeated examinations on day 7 or day 14, or earlier following clinical deterioration,[12] while Arrumugham et al. performed imaging at diagnosis, again between days 5 and 7 and subsequently when clinically indicated.[13] The latter study noted that many complications were detected after the first week. The contemporary cohort of Peros et al. provides further confirmation that sonographic manifestations of ventricular infection may progressively emerge over time.[17] These observations collectively suggest that the value of cranial ultrasonography in meningitis lies not simply in performing an initial scan, but in serial bedside surveillance.

The present study also demonstrated a strong relationship between the intensity of CSF inflammation and cranial ultrasonographic abnormalities. Abnormal sonography was observed in 90.9% of infants with CSF leukocyte counts ≥1000 cells/mm³ compared with 33.3% among those with lower counts. Similarly, abnormal sonography occurred in 90.5% of infants with CSF protein >150 mg/dL compared with 36.8% among those with lower protein concentrations. Higher CSF leukocyte count and protein were also associated with ventriculomegaly and ventriculitis. Soni et al. reported a comparable relationship, with greater sonographic abnormalities among infants with very high CSF cellularity and protein concentrations above 150 mg/dL.[12]

More recent evidence supports the relationship between an intense CSF inflammatory response and severe disease, although the precise laboratory thresholds vary between populations. Wang and Zhu studied 186 neonates with bacterial meningitis and found higher CSF protein to be associated with culture-positive disease; culture-positive infants also demonstrated more severe clinical manifestations

and neurological injury.[18] However, conventional CSF indices must be interpreted cautiously. Pelkonen et al., in a prospective study of 1088 symptomatic infants younger than 90 days, found that 25% of infants classified as having bacterial meningitis had all measured conventional CSF parameters within normal ranges.[19] Therefore, the association observed in the present study should not be interpreted to mean that low CSF inflammatory indices exclude meningitis or its complications. Rather, marked inflammatory abnormalities appear to identify a subgroup in whom closer neurological surveillance may be warranted.

Interestingly, CSF glucose did not show a significant relationship with abnormal cranial ultrasonography in the present study. Soni et al. likewise specifically reported correlation of sonographic abnormalities with CSF cell count and protein concentration, but not with CSF glucose.[12] In contrast, Peros et al. found lower CSF glucose and higher CSF protein among neonates with ventriculitis than among those with meningitis without ventriculitis.[17] These observations are not necessarily contradictory because the outcomes being examined differ: the present study evaluated the presence of any abnormal cranial ultrasonographic finding, whereas Peros et al. specifically compared infants with and without ventriculitis. CSF glucose may therefore be useful as part of the overall assessment of disease severity but appears less consistently related to the complete spectrum of sonographic abnormalities.

A major finding of the present study was the relationship between cranial ultrasonography and short-term clinical outcome. All 14 infants with normal serial cranial ultrasonography recovered without major neurological morbidity, whereas 11 of 26 infants (42.3%) with abnormal ultrasonography experienced neurological morbidity or mortality. This relationship closely resembles the findings of Arrumugham et al., in whom all 18 infants with normal ultrasonography had an uneventful recovery, while abnormal sonographic complications were associated with substantial morbidity and mortality.[13] Their overall mortality was 16%, with sequelae reported in 18% of the cohort, compared with mortality of 10.0% and neurological morbidity of 17.5% in the present study.

More contemporary imaging evidence further supports the potential prognostic importance of abnormal cranial ultrasonography. Martis et al. studied 50 neonates with Group B streptococcal meningitis and found abnormal cranial ultrasonography in 28 (56%). Ten infants died during the neonatal period. Importantly, abnormal cranial ultrasonography was associated with abnormal motor outcome, with an odds ratio of 5.3.[16] MRI demonstrated abnormalities in 27 of the 31 infants who underwent MRI, indicating both the prognostic value of imaging and the greater sensitivity of MRI for defining the extent of cerebral injury.

The prognostic significance of imaging should nevertheless not be considered absolute. Fister et al. evaluated 23 infants with neonatal Group B streptococcal meningitis and found neurological abnormalities at 18 months in nine children and epilepsy in four. In their relatively small cohort, clinical and neurophysiological markers such as impaired consciousness, hemodynamic instability, seizures and abnormal electroencephalography were stronger predictors of poor outcome, whereas laboratory and imaging abnormalities were not independently predictive.[20] The difference from the present observations may reflect their smaller GBS-specific population, different imaging protocols and, importantly, assessment of 18-month neurodevelopment rather than short-term discharge outcome. This contrasting evidence reinforces the concept that cranial ultrasonography should contribute to, rather than replace, comprehensive clinical prognostication.

Long-term follow-up is particularly important because apparently satisfactory recovery at hospital discharge does not necessarily exclude later cognitive, motor, hearing or behavioural impairment. A 2022 multicountry cohort that included children from India and other low- and middle-income settings demonstrated persistent neurodevelopmental consequences following invasive Group B streptococcal disease in early infancy.[21] Therefore, the neurological morbidity recorded at discharge in the present study is likely to represent only the early component of outcome, and longer developmental surveillance would provide a more complete assessment of disease burden.

Although cranial ultrasonography has considerable practical advantages, its limitations must also be recognized. Arrumugham et al. demonstrated good agreement between ultrasound and CT for ventriculomegaly, ventriculitis, solitary brain abscess and cerebral edema, but ultrasonography failed to detect some bilateral subdural effusions, multiple abscesses and cerebral infarctions.[13] Similarly, Martis et al. reported abnormal CUS in 56% of neonates with GBS meningitis but abnormal MRI in 87% of those who underwent MRI.[16] Consequently, a normal cranial ultrasound should not be interpreted as definitive exclusion of intracranial pathology. MRI remains appropriate when neurological deterioration, focal neurological signs, persistent seizures, unexplained clinical abnormalities or suspected complications are not adequately explained by ultrasonography.

Cerebral Doppler assessment represents another potential extension of conventional cranial ultrasonography. Okten et al. performed serial cranial Doppler ultrasonography in 33 newborns and infants with bacterial meningitis, of whom 14 developed neurological sequelae. Alterations in cerebral blood-flow velocity and pulsatility indices were associated with neurological outcome,

suggesting that Doppler parameters may provide additional physiological information beyond structural grayscale imaging.[22] Future larger prospective studies combining conventional cranial ultrasonography, cerebral Doppler indices, CSF biomarkers and structured neurodevelopmental follow-up could determine whether multimodal bedside assessment improves prognostic accuracy.

The principal strengths of the present study are its prospective design, serial rather than single-time-point ultrasonographic assessment, and simultaneous evaluation of imaging findings, CSF inflammatory parameters and short-term clinical outcome. However, the relatively small sample size limits precise assessment of uncommon abnormalities such as brain abscess, porencephalic cysts and extra-axial collections. Cranial ultrasonography is also operator-dependent and has lower sensitivity than MRI for certain infarcts, small extra-axial collections and complex parenchymal lesions. Finally, outcome assessment at hospital discharge cannot identify the entire spectrum of later neurodevelopmental impairment. Larger prospective studies incorporating standardized ultrasound protocols, Doppler assessment, MRI in selected cases and longer neurodevelopmental follow-up are therefore warranted.

In conclusion, the present findings indicate that serial cranial ultrasonography is a useful, safe and readily repeatable bedside modality for detecting and monitoring intracranial complications of bacterial meningitis in infants. Echogenic or widened sulci, ventriculomegaly, parenchymal echogenicity and ventriculitis constituted the predominant abnormalities. Higher CSF leukocyte counts and protein concentrations were associated with a greater frequency of sonographic abnormalities, whereas CSF glucose showed no comparable relationship. Most importantly, abnormal serial cranial ultrasonography was associated with a greater frequency of adverse short-term outcome. Cranial ultrasonography should therefore be regarded as a complementary component of clinical and CSF assessment, particularly for serial surveillance, while MRI remains important when complications are suspected despite inconclusive ultrasound findings.

Strengths of the study

The major strengths of the study include its prospective design and the use of serial rather than single-time-point cranial ultrasonography.

The study additionally correlated structural cranial ultrasonographic abnormalities with CSF inflammatory parameters and short-term clinical outcome, allowing imaging findings to be interpreted within the broader clinicobiochemical profile of bacterial meningitis.

Cranial ultrasonography is readily repeatable without radiation exposure or sedation, making the approach particularly relevant to neonatal and infant care and to healthcare environments where immediate access to MRI may be limited.

Limitations: The relatively small sample size of 40 infants limits the precision with which uncommon complications such as brain abscess, extra-axial collections, porencephalic cyst formation and encephalomalacia can be estimated.

Cranial ultrasonography is operator-dependent, and its diagnostic yield may vary with imaging technique, timing of examination and available acoustic windows.

Ultrasonography also has lower sensitivity than MRI for certain cortical, ischemic, posterior fossa and small extra-axial abnormalities.

Not all infants underwent CT or MRI; therefore, the study was designed primarily to evaluate the clinical utility of serial cranial ultrasonography rather than to determine its sensitivity and specificity against a universal cross-sectional imaging reference standard.

Finally, outcome was assessed at discharge. Longer neurodevelopmental follow-up would be required to identify later motor, cognitive, behavioural, hearing and developmental sequelae.

CONCLUSION

Serial cranial ultrasonography demonstrated clinically relevant intracranial abnormalities in a substantial proportion of infants with acute bacterial meningitis.

Echogenic or widened cerebral sulci and ventriculomegaly were the predominant abnormalities, followed by increased parenchymal echogenicity and ventriculitis. Importantly, several ventricular and destructive intracranial complications became apparent during subsequent examinations, supporting the value of serial rather than single-time-point imaging.

Greater CSF inflammatory severity, particularly a higher CSF leukocyte count and elevated CSF protein concentration, was associated with an increased frequency of abnormal cranial ultrasonographic findings. CSF glucose showed no comparable relationship.

Abnormal cranial ultrasonography was also associated with a higher frequency of neurological morbidity and mortality, whereas infants with persistently normal serial examinations had favorable short-term outcomes in this model cohort.

Cranial ultrasonography should therefore be considered a complementary bedside imaging modality for early assessment and serial monitoring of infants with bacterial meningitis, rather than a replacement for CSF examination or advanced neuroimaging. CT or MRI remains appropriate when the clinical condition is unexplained by ultrasonographic findings or when complications beyond the reliable diagnostic range of cranial ultrasonography are suspected.

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