Early Diagnosis and Prevention of Infections in Cirrhosis

Anand V. Kulkarni, MD, DM1, Madhumita Premkumar, MD, DM2, Juan P. Arab, MD3, Karan Kumar, MD, DM4, Mithun Sharma, MD1, Nageshwar D. Reddy, MD, DM1, Nagaraja R. Padaki, MD, DM1, Rajender K. Reddy, MD, FAASLD5

1Department of Hepatology, Asian Institute of Gastroenterology, Hyderabad, Telangana, India
2Department of Hepatology, Postgraduate Institute of Medical Education and Research, Chandigarh, India
3Departamento de Gastroenterología, Escuela de Medicina, Pontificia Universidad Católica de Chile, Santiago, Chile
4Department of Hepatology, Mahatma Gandhi Medical College and Hospital, Jaipur, Rajasthan, India
5Division of Gastroenterology and Hepatology, University of Pennsylvania, Philadelphia, Pennsylvania

Address for correspondence: Rajender K. Reddy, MD, FAASLD, Founders Professor of Medicine, Director of Hepatology, University of Pennsylvania, Philadelphia, PA 19104-6243 (e-mail: reddyr@pennmedicine.upenn.edu).

Graphical Abstract

Strategies to prevent infection and improve outcomes in patients with cirrhosis. HAV, hepatitis A virus; HBV, hepatitis B virus; COVID-19, novel coronavirus disease 2019; NSBB, nonselective β-blocker; PPI, proton pump inhibitors.

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Cirrhosis is a risk factor for infections. Approximately 50% of hospital admissions in patients with cirrhosis are due to infections. Sepsis is an immunological response to an infectious process that leads to end-organ dysfunction and death. Preventing infections may avoid the downstream complications, and early diagnosis of infections may improve the outcomes. In this review, we discuss the pathogenesis, diagnosis, and biomarkers of infection; the incremental preventive strategies for infections and sepsis; and the consequent organ failures in cirrhosis. Strategies for primary prevention include reducing gut translocation by selective intestinal decontamination, avoiding unnecessary proton pump inhibitors’ use, appropriate use of β-blockers, and vaccinations for viral diseases including novel coronavirus disease 2019. Secondary prevention includes early diagnosis and a timely and judicious use of antibiotics to prevent organ dysfunction. Organ failure support constitutes tertiary intervention in cirrhosis. In conclusion, infections in cirrhosis are potentially preventable with appropriate care strategies to then enable improved outcomes.

Source of Infections in Cirrhosis

The high incidence of BT in this population is attributed to immune dysregulation, deficiency of complement components C3 and C4, downregulation of monocyte human leucocyte antigen-DR expression, impaired Fcγ receptor-mediated clearance of antibody-coated bacteria, depressed neutrophil burst and intracellular killing, and risk of BT. In addition, the sepsis risk is worsened with the increasing severity of liver disease and is more common in decompensated cirrhosis. The pathogenesis of sepsis in cirrhosis has been described in Fig. 1.

Approximately 50% of infections are community acquired, and 25% each are health care–associated and nosocomial infections. However, 70% of severe infections in cirrhosis are nosocomial and health care acquired. Spontaneous bacterial peritonitis (SBP), urinary tract infection (UTI), skin and soft tissue infection (SSTI), and spontaneous bacteremia are frequent community-acquired infections, while UTI, lower respiratory tract infections, spontaneous bacteremia, and Clostridium difficile infections are frequent causes of health care and nosocomial infections.

Cultures are positive in 45 to 60% of patients with BS. Gram-negative bacilli (GNB), especially Enterobacteriaceae like Escherichia coli and Klebsiella pneumoniae, are more common in community-acquired infections, while gram-positive cocci (GPC), such as Enterococcus faecalis and Staphylococcus aureus, are more frequent in nosocomial infections. Patients with advanced cirrhosis often have less-virulent strains of GNB causing sepsis. Mixed infections (GNB and GPC) account for 5 to 10% of cases. Secondary fungal infections are noted in 10 to 15% of patients with cirrhosis. Due to immunoparesis in advanced liver disease, even commensal strains turn pathogenic by bypassing the mucosal defenses and cause invasive sepsis by BT. Host factors, relative to bacterial factors, play a dominant role in the pathogenesis of sepsis in patients with cirrhosis. Patients with nosocomial or hospital-acquired infections, those who have undergone invasive procedures, interventions, and/or received multiple antibiotics have higher susceptibility to gram-positive organisms.

Consequences of Infection in Cirrhosis

Infection in a patient with cirrhosis may lead to a shock state of sepsis and organ failures through one or more mechanisms:
worsening of the basal hyperdynamic state and low systemic vascular resistance, decreasing the response to α adrenoreceptor agonists, relative adrenal insufficiency, and left ventricular diastolic dysfunction.\textsuperscript{12} Acute kidney injury (AKI) occurs in about one-third of patients with cirrhosis and sepsis due to hemodynamic alterations, renal vasoconstriction, and high-circulating cytokines and is associated with poor prognosis.\textsuperscript{12,19}

Patients with decompensated cirrhosis are also predisposed to pneumonia and respiratory failure as a consequence of impaired pulmonary alveolar macrophage activity, increased pulmonary permeability, basal segment collapse due to tense ascites, alteration of T-cell subset ratio, risk of aspiration or micro aspiration due to hepatic encephalopathy or endoscopic interventions, and pulmonary microangiopathy.\textsuperscript{12,20} Patients with cirrhosis who require mechanical ventilation for severe pneumonia or acute respiratory distress syndrome have mortality rates between 60 and 80\%.\textsuperscript{3,20}

Coagulation failure with endothelial activation is also noted in patients with sepsis and cirrhosis and is due to an increase in factor VIII, von Willebrand's factor, and tissue factor with reduced levels of protein C, protein S, antithrombin III, and factors V, VII, and X.\textsuperscript{21} These changes, along with thrombocytopenia due to hypersplenism, alter the coagulation profile from a procoagulant to anticoagulant phenotype. This increases the risk of variceal and nonvariceal gastrointestinal bleeds, interventional site bleeding, and thromboses at other sites.\textsuperscript{21}

Patients with cirrhosis have vasopressin deficiency and increased levels of nitric oxide, and, further, they characteristically demonstrate preexisting arterial underfilling, reduced peripheral vascular resistance, and high cardiac output.\textsuperscript{22,23} Sepsis exacerbates these hemodynamic abnormalities and worsens cardiac dysfunction and tissue hypoperfusion.\textsuperscript{24} Sepsis
further augments the hyporesponsiveness to exogenous vaso-
pressor and increases the sensitivity to nitric oxide, leading to
shock.23 The presence of relative adrenal insufficiency also
contributes to hypotension in patients with cirrhosis.25

Cerebral failure due to systemic and neuroinflammation
can result in “septic encephalopathy” in 30 to 60% of patients
with cirrhosis and sepsis.26 In addition, hyperammonemia,
systemic inflammatory response syndrome (SIRS), and cyto-
kine storm exacerbate cerebral edema.27

Liver dysfunction evolves within 2 hours of sepsis onset in
animal models.28 Liver dysfunction is noted in up to 40% of
patients with sepsis and cirrhosis, but liver failure in sepsis in
those without cirrhosis is under 10%.29 In those without
cirrhosis, the liver can withstand this injury due to its high
regenerative capability as opposed to those with cirrhosis.
Furthermore, endotoxin-mediated cytokine burst leads to
rapid impairment in hepatic microcirculation, increased
hepatic oxidative stress, and neutrophil infiltration.30
Thus, sepsis in cirrhosis can quickly lead to hepatocyte death
and liver failure.

Diagnosis of Infection and Consequent Sepsis in Cirrhosis

The diagnosis of sepsis is challenged by the currently avail-
able heterogeneous definitions in patients with cirrhosis.31
Sepsis was previously defined as SIRS with proven infec-
tion.32 Approximately 50 to 60% of patients with cirrhosis
and infection have SIRS.33,34 Hypersplenism and β-blocker
therapy may impair the ability to rise in white cell count
(WCC) and heart rate. Furthermore, 10 to 30% of patients
with decompensated cirrhosis without BI demonstrate fea-
tures of SIRS due to a hyperdynamic circulation, altered
mentation, and/or tense ascites that affect the pulse rate,
respiratory rate, and temperature.33 Although SIRS is associ-
ated with poor outcomes in cirrhosis, it is insufficient to
predict or define sepsis.31,34

According to the latest SEPSIS-3 guidelines, sepsis is
defined as life-threatening organ dysfunction caused by a
dysregulated host response to infection.5 Organ dysfunction
is identified by an acute change in sequential organ failure
assessment (SOFA) score by 2 points or higher. This criterion
is well-validated and applicable to ICU patients with cir-
rhosis.35 However, it is known that sepsis leads to organ
dysfunction, and patients present with extrahepatic organ
failures.8,9 Hence SOFA scores may not be appropriate
for sepsis diagnosis at admission or bedside.16 Conversely,
the severity scores, such as chronic liver failure–SOFA
(CLIF-SOFA) and consortium organ failure score (CLIF-
COF) aid in predicting outcomes in patients with sepsis-
related organ failure.37 However, these severity scores can
neither predict sepsis nor diagnose sepsis. Instead, they are
aimed to predict survival and requirement for transplanta-
tion in ACLF.

Recently quick SOFA (qSOFA) has been developed to
diagnose sepsis, and this is independently related to survival
and is used as a bedside tool.35,36 Altered mentation, systolic
blood pressure 100 mm Hg or lower, and respiratory rate 22
breaths/min or higher constitute qSOFA. Thus, dynamic
changes in qSOFA may predict the survival in patients with
cirrhosis and infection.36 Furthermore, fever is a classical
sign of infection. Therefore, we consider a combination of
fever and qSOFA as a valuable bedside tool to predict sepsis.
A proposed approach to diagnose sepsis in patients with
cirrhosis is provided in – Fig. 2. The definition of each
infection event is outlined in the footnotes of – Fig. 2.15,38

Key point: fever and qSOFA are simple bedside tools to
identify sepsis in patients with cirrhosis.

Biomarkers of Infection and Consequent Sepsis

A promising biomarker should be economical, readily avail-
able, and sensitive enough to detect infection in cirrhosis.
Several biomarkers have been evaluated in patients with
cirrhosis, such as WCCs, procalcitonin (PCT), C-reactive
protein (CRP), interleukin (IL)-6, neutrophil-to-lymphocyte
cycle ratio (NLR), presepsin, resistin, and high-density lipoprotein
(HDL).39,40 Of these, NLR is a simple biomarker that can predict
infections and outcomes in patients with cirrhosis,41,42 Bl-
induced rise in the neutrophil population and suppression of
lymocyte cells leads to high NLR.43 An NLR of greater than
8.3 is suggestive of infection in cirrhosis; a higher NLR is
predictive of organ failures in cirrhosis. Other leucocyte ratios,
including monocyte-to-lymphocyte cycle ratio (MLR), are also
known to predict mortality in patients with cirrhosis and
sepsis; however, these need further validation.41

On the contrary, CRP and IL-6 may not be suitable markers
for diagnosing sepsis in cirrhosis, as the liver is either the
source of production or a clearance site. In addition, organ
dysfunction in sepsis may also alter the levels of these
markers due to reduced clearance in the presence of renal
failure (e.g., PCT). Further, the use of all sepsis biomarkers is
fraught with significant overlap in the diagnostic range for
SIRS and sepsis. Despite these limitations, CRP and PCT are
frequently used to diagnose sepsis and have been assessed
across multiple studies.43 A cut-off values of greater than 25
and greater than 0.5 ng/mL for CRP and PCT, respectively, are
significant for the diagnosis of sepsis.43 However, utilizing
these in combination with clinical evidence is crucial for the
correct identification of sepsis.

HDL-related biomarkers (HDL-C and apoA-1) are signifi-
cantly lower in infected patients with cirrhosis.44 They
negatively correlate with inflammatory markers such as
CRP, WCCs, IL-6, IL-8, and tumor necrosis factor (TNF)-α.
These biomarkers can predict infections and survival.44–47
HDL and its scavenger receptor B1 can neutralize endotox-
ins.48 A lower HDL may increase the risk of sepsis.49
Presepsin is the N-terminal fractional protein resulting
from cleavage of CD14 receptor and endotoxin (ligand)
cleaved by inflammatory serum proteases.49 Resistin is a
hormone produced by macrophages and adipocytes that
correlates directly with inflammatory markers CRP and
TNF-α and negatively with survival in patients with
cirrhosis.50 Thus, presepsin and resistin can also accurately
diagnose sepsis.49 Bl activates the triggering receptor
Markers of Infection Not Validated in Patients with Cirrhosis

High-mobility group box-1 (HMGB-1) is a well-known damage-associated molecular pattern (DAMP) involved in regulating gene expression.59 Recent studies have demonstrated that elevation in HMGB-1 (> 5.9 ng/mL) in patients with sepsis can predict mortality.60 In addition, angiopoietin-1 and 2 soluble receptor for advanced glycation end products (sRAGE), and soluble urokinase-type plasminogen activator receptors (suPAR) are other markers that also aid in predicting outcomes.61 However, studies in patients with cirrhosis are lacking for these novel markers.

Key point: PCT, CRP, and NLR can aid in diagnosing sepsis in patients with cirrhosis.
### Table 1  Biomarkers of infection and consequent sepsis in cirrhosis

<table>
<thead>
<tr>
<th>Biomarker</th>
<th>Cut-off</th>
<th>Comments</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLR</td>
<td>8.3 in patients with infection</td>
<td>Ability to predict mortality and organ failures in patients with sepsis</td>
<td>Advantages: easy to calculate. Limitations: optimal cut-off value for predicting sepsis is unclear</td>
</tr>
<tr>
<td>PCT</td>
<td>0.5 ng/mL</td>
<td>MW: 14.5 kDa Peptide precursor of the hormone calcitonin Source: Thyroid Detectable 1–4 hours after infection Half-life: 20–24 hours</td>
<td>Advantages: easily available. Validated across multiple studies. Limitations: increased in renal failure and inflammation</td>
</tr>
<tr>
<td>CRP</td>
<td>25 ng/mL</td>
<td>MW: 120 kDa Acute phase protein Source: Liver Rise within 6 hours of infection Half-life: 19 hours</td>
<td>Advantages: easily available. Validated across multiple studies. Limitations: increased in inflammation, long half-life. Remains elevated for a prolonged duration (36 hours)</td>
</tr>
<tr>
<td>IL-6</td>
<td>Varying cut-off IL-6 &gt; 35 pg/mL with fever suggestive of sepsis</td>
<td>MW: 23 kDa Source: leucocytes, fibroblasts, monocytes, macrophages, T-cells and endothelial cells Rises within 2–4 hours of injury (inflammation) Half-life: &lt; 1 hour</td>
<td>Needs further validation</td>
</tr>
<tr>
<td>HDL-c</td>
<td>&lt; 30 mg/dL predicts infection &lt; 17 mg/dL predicts mortality</td>
<td>Lipoproteins with a density ranging from 1.063 to 1.21 Pleiotropic effect: LPS neutralization, endothelial protection, and antioxidant and anti-apoptotic properties</td>
<td>Advantages: can be easily measured. Limitations: requires further validation. Levels inversely correlates with liver disease</td>
</tr>
<tr>
<td>Apo-AI</td>
<td>&lt; 75 predicts infections &lt; 50 mg/dL predicts mortality</td>
<td>Protein component of HDL-c Potent antioxidant and anti-inflammatory properties</td>
<td>Limitations: not routinely available at all centers. Inversely correlates with liver disease</td>
</tr>
<tr>
<td>Presepsin</td>
<td>1,444 pg/mL for diagnosing sepsis</td>
<td>MW: 13 kDa N-terminal fractional protein resulting from cleavage of CD14 receptor and endotoxin (ligand) cleaved by inflammatory serum proteases Half-life: 4–5 hours Detectable within 2 hours of infection Plasma levels of presepsin can be considered as an indicator of activated innate immune effector cells in response to invasive pathogens</td>
<td>Advantages: accuracy similar to PCT and CRP. Limitations: not routinely available at all centers. Requires further validation</td>
</tr>
<tr>
<td>Resistin</td>
<td>20 ng/mL</td>
<td>MW: 12.5 kDa A pro-inflammatory adipokine Mainly derived from macrophage and adipocytes Half-life: 5 hours</td>
<td></td>
</tr>
<tr>
<td>sTREM-1</td>
<td>430 pg/mL predicts infection &gt; 600 pg/mL can predict mortality in infected cirrhosis patients</td>
<td>MW: 15 kDa Soluble form of TREM-1 Source: neutrophils, monocytes, and macrophages Peak levels at 2 hours after infection Short half-life: (12 minutes- in vivo)</td>
<td>Can predict mortality and organ dysfunction. Not widely available for routine use</td>
</tr>
<tr>
<td>sCD163</td>
<td>&gt; 7,000 can predict mortality in infected cirrhosis patients 4,586 in patients with infection</td>
<td>MW: 130 kDa Source: activated macrophages (Kupffer’s cells) and monocytes. Activation time: 2 hours Half-life: 12–24 hours Correlates directly with IL-6, 8, and 10</td>
<td>Advantages: predicts mortality and correlates with organ failures in BI in patients with cirrhosis. Limitations: not available for routine use</td>
</tr>
<tr>
<td>MR-proADM</td>
<td>MW: 5.1 kDa Precursor peptide of adrenomedullin, a va- soactive calcitonin peptide family member that is rapidly cleared from circulation Source: endothelial cells and vascular smooth muscle cells Half-life-hours compared with 22 minutes for ADM</td>
<td>Correlates with CRP, IL-6 and WCC and organ dysfunction. More sensitive for SBP than other bacterial infections. Limitations: cut-off values unknown. Not routinely available at all centers</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: ADM, adrenomedullin; apoA-I, apolipoprotein A-I; CRP, C-reactive protein; HDL, high-density lipoprotein; IL, interleukin; MR-proADM, mid-regional proadrenomedullin; MW, molecular weight; NLR, neutrophil-to-lymphocyte ratio; PCT, procalcitonin; SBP, spontaneous bacterial peritonitis; sCD, soluble cluster differentiation; sTREM-1, soluble triggering receptor expressed on myeloid cell-1; WCC, white cell count.

Note: References for cut-off values. Bernsmeier et al (NLR)41; Jalan et al (PCT and CRP)43; Li et al (IL-6)40; Trieb et al (HDL and apoAI)44; Fischer et al (Presepsin and resistin)49; Tornai et al (sTREM1)51; Tornai et al (sCD163).52
Novel Molecular Techniques for Diagnosis of Infection

Since the routine culture-based techniques for the infectious organism are laborious and time consuming, there is an increased risk of patients being exposed to empirical antibiotics for a longer duration which may lead to poor outcomes and increase the risk of multidrug resistant organisms (MDROs). This drawback can be overcome with newer molecular techniques that quickly identify the causative organism with a small amount of clinical specimens. Nucleic acid amplification tests with or without microarray, fluorescent in situ hybridization (FISH), and matrix-assisted laser desorption ionization-time of flight mass spectrometry (MALDI-TOF MS) are novel molecular techniques for rapid detection of microorganisms from signal positive blood culture (Table 2). There are also a few point-of-care (POC) tests to detect microorganisms and resistance patterns. Examples of such POC tests are Curetis Unyvero, RAPIDEC CARBA NP, and MinION. The limitation of these novel tests is that they detect the DNA of microorganisms and not the live pathogens, and the presence of background DNA in blood, lack of ideal gold standard, and contamination of the sample may compromise the interpretation of the molecular tests.\(^{62}\) Lastly, none of these expensive tests have been validated in patients with cirrhosis. However, these novel techniques may reduce the risk of improper antibiotic exposure in patients with cirrhosis who are prone for infections with MDROs and polymicrobial organisms. Rapid diagnosis of infection and susceptibility profiles may improve the outcomes of these critically ill patients through timely deescalation/escalation of antibiotics.

**Prevention of Infection**

Prevention of infection may improve the quality of life, prolong survival, and reduce hospital admissions and cost burden. Prevention of infection can be through general measures of exercise, and enhanced nutrition across the various stages of cirrhosis, primary prevention, secondary prevention, and tertiary intervention may help in managing the consequences of infection (Fig. 3).

**Primary Prevention**

Prevention of infection (or relapse of same or similar infection) in a patient with cirrhosis constitutes primary prevention. Pneumonia (both viral and bacterial) is a frequent cause and is associated with high mortality.\(^{53,64}\) In addition, superimposed viral hepatitis A and B is associated with increased morbidity and mortality in patients with cirrhosis.\(^{55,66}\) Novel coronavirus disease 2019 (COVID-19) is also known to precipitate organ failures in patients with cirrhosis.\(^{67,68}\) Therefore, all patients with cirrhosis should be vaccinated for influenza, pneumococci, hepatitis A and B, and COVID-19.\(^{56,69–71}\)

A reduction in gut translocation by nutritional intervention, immunonutrition, selective intestinal decontamination (with prophylactic antibiotics), avoidance of unnecessary proton pump inhibitors, and timely use of β-blockers and experimental granulocyte–colony stimulating factor (G-CSF) therapy constitutes primary prevention. Long-term albumin infusions and norfloxacin prophylaxis to prevent infection/ reinfection are part of a primary prevention strategy.\(^{72,73}\) In addition, simvastatin may also prevent sepsis and curb the inflammatory response in patients with cirrhosis.\(^{74}\) Finally, adequate control of ascites, pedal edema, and appropriate skincare may prevent SSTIs. Sarcopenia is known to be associated with poor outcomes in patients with cirrhosis and infections for which balanced nutrition and exercise can improve outcomes.\(^{75}\) In addition, universal precautions, such as maintaining hand hygiene, avoiding unnecessary instrumentation, use of aseptic techniques, and careful measures

**Table 2** Novel techniques for rapid diagnosis of infection

<table>
<thead>
<tr>
<th>Principle</th>
<th>Name of the test</th>
<th>Turnaround time (min)</th>
<th>Number of organisms isolated</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAAT by real-time PCR ± microarray</td>
<td>Verigene</td>
<td>150</td>
<td>13 gram positive; 9 gram negative organisms including resistance testing for mecA, vanA/B, IMP, KPC, NDM, OXA, CTX-M</td>
</tr>
<tr>
<td>Biofire Filmarray</td>
<td>60</td>
<td>8 gram positive (resistance genes: mecA, vanA/B) 11 gram negative organisms (resistance genes: KPC) 5 candida species</td>
<td></td>
</tr>
<tr>
<td>SeeGene Magicplex</td>
<td>360</td>
<td>73 gram positive (resistance genes: mecA, vanA/B) 12 gram negative organisms and 6 candida species</td>
<td></td>
</tr>
<tr>
<td>Lightcyt SeptiFast</td>
<td>360</td>
<td>6 gram positive, 10 gram negative and six fungi</td>
<td></td>
</tr>
<tr>
<td>XPERT MRSA/SA</td>
<td>60</td>
<td>MRSA and MSSA</td>
<td></td>
</tr>
<tr>
<td>FISH</td>
<td>AdvanDx QuickFISH</td>
<td>30</td>
<td>2 gram positive, 3 gram negative, all Enterococcus and 3 candida species</td>
</tr>
<tr>
<td>Accelerate Phenotest</td>
<td>90</td>
<td>6 gram positive, 8 gram negative, and 2 candida species</td>
<td></td>
</tr>
<tr>
<td>MALDI-TOF MS</td>
<td>Bruker’s Sepsityper Vitek MS</td>
<td>15–20</td>
<td>Wide range dependent on database</td>
</tr>
</tbody>
</table>

Abbreviations: FISH, fluorescent in situ hybridization; MALDI-ToF, Matrix-Assisted Laser Desorption Ionization-Time of Flight Mass Spectrometry; MSSA, methicillin sensitive staphylococcus aures; NAAT, nucleic acid amplification test; PCR, polymerase chain reaction.
to prevent catheter-related infections, must be undertaken in all patients to prevent infections.

**Beta-Blockers**

Nonselective β-blocker (NSBB) therapy reduces the likelihood of complications of cirrhosis (including ascites, SBP, and hepatic encephalopathy) and prolongs survival. NSBBs have the potential to increase intestinal transit time by blocking β-3 receptors. Furthermore, NSBBs counteract altered mucosal perfusion and integrity by reducing portal pressure and intestinal permeability, further reducing endotoxemia. SBP is a common cause of sepsis in cirrhosis. NSBB, especially propranolol, has been reported to prevent SBP in patients with decompensated cirrhosis. However, studies on NSBBs in decompensated cirrhosis are limited by small sample sizes and heterogeneous populations. Furthermore, the safety of β-blockers in patients with advanced liver disease is still questionable, given the potential consequences of reduction in cardiac output. Several relative contraindications for the use of NSBB in decompensated cirrhosis, such as hyponatremia, refractory ascites, hypotension, infections, and AKI, have been suggested.

In a recent randomized controlled trial, prophylactic NSBBs in patients with compensated cirrhosis noted prevention of ascites, the most common decompensation in the natural history of cirrhosis. However, prophylactic NSBBs could not prevent SBP or other site infections. Nevertheless, NSBBs has the potential to reduce the risk of decompen-sation and infections in patients with cirrhosis by preventing BT.

**Key point:** as part of primary prevention, prophylactic NSBBs in carefully selected patients with decompensated cirrhosis may prevent BT and consequent infections.

**Proton Pump Inhibitors**

Proton pump inhibitors (PPIs) reduce gastric pH and motility and promote small intestinal bacterial overgrowth. PPIs (especially prolonged use) increase the risk of infections, such as SBP and *C. difficile* in cirrhosis, and adversely affect the outcomes. Hence, it may be prudent to avoid long-term PPIs in patients with cirrhosis.

**Albumin**

Elevated prostaglandin E₂ (PGE₂) and hypoalbuminemia lead to immunosuppression and infection susceptibility in acutely decompensated cirrhosis. Albumin modulates lipopolysaccharide (LPS) presentation by modulating toll-like receptor (TLR)-4 expression, promoting bacterial killing by binding PGE₂, and preventing endothelial dysfunction due to LPS. Patients with cirrhosis have inadequate PGE₂ binding capacity and consequently have immune dysfunction. Treatment
with 20% human albumin solution (HAS) has been shown to bind more PGE2 and reverse plasma-mediated immune dysfunction. Ischemia-modified albumin, a posttranslational functional alteration in the N-terminus of albumin, is found more frequently in patients with cirrhosis, and HAS supplementation may help rebalance it. Studies on long-term HAS administration have shown variable results. Long-term HAS administration (for outpatients) can prevent SBP- and non-SBP-related infections and reduce the incidence of kidney dysfunction. Long-term HAS can also prevent hospital admissions, ascites recurrence, and prolong survival. In addition, long-term albumin administration has an immunomodulatory effect in patients with decompensated cirrhosis. Hence, in patients with decompensated cirrhosis, long-term HAS may reduce the incidence of sepsis-triggered ACLF by reducing infections. However, the results of the ANSWER study were contradicted by the MACTH study which concluded that HAS (and midodrine) supplementation could not prevent complications of cirrhosis. It may be argued that the patients included in the MACTH trial were those with more advanced disease, a higher MELD score, and received HAS therapy for a brief duration. Studies on long-term HAS administration in sepsis are shown in Table 3.

Key point: long-term albumin therapy may prevent precipitation of sepsis-triggered ACLF in patients with decompensated cirrhosis. However, further studies are needed to ascertain the same.

Antibiotics
Cirrhosis is associated with dysbiosis in the intestinal flora with an overgrowth of pathogenic flora and reduced autotchnous bacterial flora. Further, the leaky gut increases the risk of BT and endotoxemia. This endotoxin-induced nitric oxide synthase (iNOS) production can exacerbate preexisting arterial vasodilation. Selective intestinal decontamination (SID) with antibiotics (especially norfloxacin) inhibits GNB and endotoxemia. Norfloxacin has been proven to prevent SBP and also infections in patients with gastrointestinal hemorrhage. Norfloxacin has favorable pharmacodynamics and pharmacokinetics. The slow solubility, low permeability, and low systemic bioavailability of norfloxacin make it an ideal choice for SID. Furthermore, norfloxacin can reduce the LPS translocation-induced rise in iNOS, aortic Akt activity, and proinflammatory cytokine release and control systemic vasodilation. Primary prophylaxis is recommended for patients with decompensated cirrhosis with serum bilirubin 3.0 mg/dL or higher and low ascitic fluid protein (<1.5 g/dL) and renal dysfunction (serum creatinine ≥1.2 mg/dL or blood urea nitrogen ≥25 mg/dL or serum sodium ≤130 meq/dL).

Norfloxacin prophylaxis is reported to be associated with three major adverse outcomes as follows: (1) increased risk of infections by gram-positive organisms; (2) increased risk of C. difficile infections; and lastly, (3) increased risk of development of MDROs. Norfloxacin prophylaxis can be associated with asymptomatic intestinal colonization with MDROs which could contribute to an increased risk of MDRO infections and nosocomial spread of MDROs. A recent study reported a reduction in the incidence of BIs in patients receiving prophylactic norfloxacin therapy without the added risk of infections by MDROs. Furthermore, a multicenter intercontinental study that included more than 1,300 patients reported that norfloxacin prophylaxis is not associated with an increased risk of MDROs. On the contrary, systemic antibiotics administered in the previous 3 months for at least 5 days, an invasive procedure during the last month and health care exposure were associated with a higher risk of MDRO development. As such, the presence of MDROs in cirrhosis is associated with a poorer prognosis; thus, early diagnosis and treatment are crucial. Norfloxacin prophylaxis should be initiated in patients meriting prophylaxis, and a high index of suspicion for MDROs in such patients admitted for infections is necessary.

Oral ciprofloxacin and trimethoprim-sulfamethoxazole are safer alternatives to norfloxacin in countries where norfloxacin is unavailable. Administered once weekly, 750 mg of ciprofloxacin is as effective as norfloxacin in the prevention of SBP. The efficacy of once weekly ciprofloxacin needs further extensive double-blind, randomized studies. However, a once weekly regimen may be preferred in patients deemed less compliant with medications and avoid pill burden.

Rifaximin is another poorly absorbed gut-sterilizing antibiotic currently recommended to prevent recurrent episodes of hepatic encephalopathy in patients with cirrhosis. Multiple small studies have demonstrated beneficial effects on the prevention of SBP in patients treated with prophylactic rifaximin. However, the low quality of evidence does not support the role of primary prophylaxis with rifaximin for SBP prevention.

Key point: prophylactic antibiotics, as part of primary prevention, may reduce the incidence of infections.

Statins
Impaired immune response, increased thrombogenesis, and systemic inflammation are common to atherosclerosis and sepsis. Statins inhibit cholesterol synthesis by inhibiting hydroxy methylglutaryl coenzyme A reductase (HMG CoA). In the process, the intermediate products of cholesterol, such as mevalonate, farnesyl pyrophosphate, and geranyl pyrophosphate, which play a crucial role in several intracellular signaling pathways, are also reduced. Hence, statins have pleiotropic effects including anti-inflammatory, anti-apoptotic, and vasoprotective properties.

Statins function to accomplish the following: activate and increase heme oxygenase-1, an inducible and heat-shock cytoprotective protein; decrease nitric oxide overproduction and prevent endotoxic shock; protect hepatic microvascular circulation and prevent endotoxin-induced intrahepatic endothelial dysfunction and hepatocyte death; decrease the effect of sepsis-induced coagulopathy through their antithrombotic properties, and improve hepatic mitochondrial activity in sepsis.

Through these mechanisms, statins can prevent various bacterial, viral, and fungal infections. However,
studies evaluating the role of statins in preventing sepsis in patients with cirrhosis are limited (Table 4).124–128 In a propensity-matched cohort (matched for age, gender, and β-blocker therapy) of patients with compensated cirrhosis, statin therapy reduced the risk of severe infections requiring hospitalization by 33% among 1,760 patients who received statin therapy compared with that of 1,760 patients who did not receive statins.124 Simvastatin was the most commonly used drug.124

Key point: statin (especially simvastatin) may be useful for primary prevention of infection.

### Granulocyte–Colony Stimulating Factor

There are conflicting reports on the benefits of G-CSF in preventing sepsis in patients with cirrhosis. The mobilization of CD34+ cells from the bone marrow to the liver, leading to regeneration and improved neutrophil function, is purported to change the hepatic microenvironment to favor regeneration and improved neutrophil function, is purported to change the hepatic microenvironment to favor regeneration and improved neutrophil function.129,130 Furthermore, with G-CSF therapy, intrahepatic and circulating dendritic cells are increased with a decrease in interferon (IFN)-γ secreting CD8 T-cells leading to a reduction in the inflammatory response.131

### Table 3 Trials on long-term use of human albumin in patients with cirrhosis

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Study (year), country</th>
<th>Study population</th>
<th>Dose and duration</th>
<th>Outcome</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gentilini et al (1999), Italy</td>
<td>126 cirrhosis patients with ascites Randomized to albumin plus diuretics versus diuretics alone</td>
<td>HAS 12.5 g/day for 7 days Weekly albumin infusion of 25 g in the first year, followed by 25 g every 2 weeks up to 3 years</td>
<td>Ascites recurrence: 19, 56, 69% in HAS versus 30, 79, and 82% in SOC at 12, 24, and 36 months Hospital readmission: 5, 56, 69% in HAS versus 27, 74, and 79%, in SOC at 12, 24, and 36 months</td>
<td>Infection and AKI not noted on follow-up Small sample size</td>
</tr>
<tr>
<td>2</td>
<td>Romanelli et al (2006), Italy</td>
<td>100 cirrhosis patients with first-onset ascites randomized to HAS + diuretics versus diuretics alone</td>
<td>HAS 25 g/week in the first year and 25 g every 2 week thereafter</td>
<td>Sepsis: 2 versus none HRS: 1 versus none Ascites recurrence: 51 versus 94%</td>
<td>Median follow-up: 84 (range: 2–120) months Limitations: small sample size</td>
</tr>
<tr>
<td>3</td>
<td>Caraceni et al (2018), Italy</td>
<td>431 patients with cirrhosis and uncomplicated ascites, MELD: HAS: 12 (10–15) SOC: 13 (10–16)</td>
<td>HAS: 40 g twice weekly for 2 weeks, and then 40 g weekly for up to 18 months</td>
<td>HAS: reduced the incidence of SBP and non-SBP bacterial infections, renal dysfunction, HRS, hepatic encephalopathy grade 3 or 4, and potential diuretic-induced side-effects by 30 to 67.5% compared with SOC alone HAS: reduced number and duration of hospital admissions</td>
<td>Adherence to therapy is real-world practice is questionable</td>
</tr>
<tr>
<td>4</td>
<td>Solà et al (2018), Spain</td>
<td>196 patients with cirrhosis and ascites awaiting liver transplant MELD: Midodrine + HAS 16 ± 6.2 SOC: 17 ± 6</td>
<td>Midodrine (15–30 mg/day) and albumin (40 g/15 days) for 1 year</td>
<td>Sepsis: 14 versus 15% in M + A group versus placebo (p: 0.805) AKI: 14 versus 13% in M + A group versus placebo (p: 0.846)</td>
<td>Midodrine + HAS was neither associated with a decrease in the incidence of complications of cirrhosis nor with improvement in survival Included high MELD patients. Received therapy for only 80 (30–244) days</td>
</tr>
<tr>
<td>5</td>
<td>Di Pascoli et al (2019), Italy</td>
<td>70 patients of cirrhosis with refractory ascites MELD: HAS 15.2 ± 5.4 SOC: 14.9 ± 5</td>
<td>HAS 20 g twice per week (mean dose: 60.7 ± 15.2 g) for a mean duration of 408 ± 394 days</td>
<td>SBP: 7.9 versus 50.6% in albumin versus SOC group No SBP infection: 27.2 versus 88.6% in albumin versus SOC group HRS: 22.5 versus 57.7% in albumin versus SOC group</td>
<td>Nonrandomized trial Liable for bias Small sample size</td>
</tr>
<tr>
<td>6</td>
<td>Sharma et al (2021), India</td>
<td>42 patients recovered from HRS-AKI</td>
<td>Midodrine 15 mg + HAS 2-g weekly versus HAS 20 g weekly for 2 months</td>
<td>AKI: 18% in M + HAS versus 50% in HAS M + HAS also reduced the frequency of taps. (1.9 ± 0.5 vs. 2.6 ± 0.5)</td>
<td>Small sample size Nonrandomized study. Prone for bias and type-II error</td>
</tr>
</tbody>
</table>

Abbreviations: AKI, hepatorenal syndrome; HAS, human albumin solution; HRS, hepatorenal syndrome; MELD, model for end-stage liver disease; SBP, spontaneous bacterial peritonitis; SOC, standard of care.
<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Study (year), country</th>
<th>Type of study</th>
<th>Population</th>
<th>Statin and dose</th>
<th>Impact on progression of liver disease</th>
<th>Impact on infection/sepsis</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motzkus-Feagans et al(^{124}) (2013), the United States</td>
<td>Retrospective</td>
<td>Patient with alcohol or HCV related cirrhosis without decompensation (n = 19,379) Statin user: 2,468</td>
<td>90.6% were on simvastatin Median duration of statin therapy-1194 (365–3103 days)</td>
<td>–</td>
<td>In the propensity-matched sample, statin users experienced lesser hospitalizations for severe infections: AHR: 0.67 (95% CI: 0.47–0.95) than nonusers.</td>
<td>Other cholesterol-lowering agents had no effect</td>
</tr>
<tr>
<td>2</td>
<td>Mohanty et al(^{126}) (2016), the United States</td>
<td>Retrospective</td>
<td>685 statin users were matched with 2,062 nonusers</td>
<td></td>
<td></td>
<td>AHR for decompensation among statin users: 0.55 (95% CI, 0.39–0.77) SBP: HR = 0.93 (95% CI: 0.29, 2.90)</td>
<td>Statins could not prevent SBP</td>
</tr>
<tr>
<td>3</td>
<td>Abraldes et al(^{125}) (2016), Spain</td>
<td>Double-blind placebo-controlled randomized trial</td>
<td>158 cirrhosis patients with history of variceal bleed</td>
<td>Simvastatin 20 mg/day the first 15 days, 40 mg/day</td>
<td>No reduction of variceal bleed.</td>
<td>SBP 3.8% in placebo arm versus 0 in statin group</td>
<td>Simvastatin is associated with survival benefit in child A and B due to reduced risk of infections</td>
</tr>
<tr>
<td>4</td>
<td>Wong et al(^{128}) (2017), Hong Kong</td>
<td>Population-based cohort study</td>
<td>Compensated cirrhosis (HBV predominant) 67,131 nonstatin users versus 2,053 statin users</td>
<td>86% simvastatin</td>
<td>45% reduction in composite end-point of variceal bleed, ascites and SBP largely driven by reduction in ascites and not variceal bleed or SBP</td>
<td>6 (0.3%) events in statin users versus 298 (0.45%) in nonstatin users</td>
<td>Reduced decompensations. Improved survival. No reduction in SBP</td>
</tr>
<tr>
<td>5</td>
<td>Bishnu et al(^{127}) (2018), India</td>
<td>Open-label RCT</td>
<td>Propanol: 12 patient Propanol + atorvastatin: 11</td>
<td>Atorvastatin 20-mg daily for 1 year</td>
<td></td>
<td>SBP in 8.33% in propanol group versus 0 in combination group</td>
<td>Limitations: small sample size</td>
</tr>
<tr>
<td>6</td>
<td>ClinicalTrials.gov identifier: NCT03780673</td>
<td>Placebo-controlled double-blind randomized study</td>
<td>240 decompensated cirrhosis patients</td>
<td>Simvastatin 20 mg/day plus rifaximin 400-mg TID for 12 months</td>
<td>Incidence and severity of ACLF. Incidence and number of episodes of decompensation (ascites, bleed, encephalopathy)</td>
<td>Incidence of bacterial infection at 12 months</td>
<td>Underway</td>
</tr>
</tbody>
</table>

Abbreviations: ACLF, acute on chronic liver failure; AHR, adjusted hazard ratio; HBV, hepatitis B virus; HCV, hepatitis C virus; RCT, randomized controlled trial; SBP, spontaneous bacterial peritonitis.
Secondary Prevention

Secondary prevention includes strategies to prevent infection-induced organ dysfunction. The early identification of sepsis and timely and judicious use of antibiotics in patients with cirrhosis can avoid the consequences of infection.

Antibiotics

Appropriate empirical antibiotics have a significant role in patients with cirrhosis and sepsis. Early appropriate antibiotic initiation may prevent organ failures. A delay in 1 hour in initiating antibiotic therapy may increase the risk of mortality by nearly 7%. A broad-spectrum empirical antibiotic use with imipenem/cilastatin with or without vancomycin has been associated with significant improvement in survival in patients with cirrhosis and severe sepsis. Furthermore, a broad-spectrum empirical antibiotic has been associated with a shorter duration of hospital stay and was more economical than the standard treatment. The proper use of empirical antibiotics may also prevent the development of BI-induced ACLF. Appropriate antibiotic therapy has led to a lower progression rate of ACLF grade (fewer patients with appropriate antibiotic therapy progressed to grade 2–3) and improved survival. On the contrary, inappropriate empirical use of glycopeptides increases the risk of mortality in patients with BI-induced ACLF. Therefore, empirical antibiotic administration and timely antibiotic de-escalation are of paramount importance in patients with cirrhosis. However, there is a lack of studies on antibiotic stewardship in patients with cirrhosis.

Key point: Appropriate empirical antibiotics, as part of secondary prevention, are associated with improved survival and outcomes in patients with cirrhosis and severe sepsis.

Albumin

Prophylactic HAS is recommended for patients with SBP to prevent AKI. However, the role of albumin in improving outcomes in hospitalized patients with non-SBP sepsis is contentious. A recent study reported no beneficial effects with supplementation of HAS in hospitalized patients with decompensated cirrhosis. The patients included were sick and received albumin only for a median duration of 8 days. The high dosing used in the study led to a significant number of patients developing fluid overload. However, it is known that low baseline serum albumin is associated with a higher incidence of sepsis and mortality. In addition, patients who develop a second infection have lower baseline serum albumin than those who do not develop them. Furthermore, albumin administration can prevent kidney injury, nosocomial infections, and lead to a better progression of ACLF grade.

Key point: Albumin administration in patients with SBP prevents renal injury. Further studies are required to assess the role of albumin, administered both in inpatients and outpatients, in preventing infections and infection-triggered multiorgan failure.

Statins

In preclinical models of infection-induced ACLF, simvastatin prevented organ dysfunction and prolonged survival. A recent retrospective study demonstrated that statin therapy was associated with a lower rate of infections and a reduction in the risk of hospitalizations for ACLF events in patients with cirrhosis. A trial of simvastatin (20 mg/day) and rifaximin (400-mg TID) for 12 months in decompensated cirrhosis to prevent ACLF is underway (ClinicalTrials.gov identifier: NCT03780673). Further research is required to confirm whether simvastatin can be used for the secondary prevention of complications of sepsis–induced ACLF, especially in patients with decompensated cirrhosis who have a high risk of rhabdomyolysis.

Key point: As part of the secondary preventive strategy, further studies are required to confirm the role of simvastatin in preventing the consequences of sepsis–induced ACLF.

Tertiary Intervention

Tertiary intervention comprises organ failure support, such as renal replacement therapy, vasopressor therapy, and mechanical ventilation, in patients with cirrhosis and sepsis.

Nutrition in Cirrhosis to Prevent Infection

Protein-energy malnutrition is common in patients with cirrhosis due to altered nutrient utilization, that is, increased fat and protein utilization and decreased carbohydrate utilization. Further, cirrhosis (especially decompensated cirrhosis) is a catabolic state associated with rapid muscle loss that may impact the outcome. Protein-energy malnutrition leads to impairment in T-cell response, hypocomplementemia, and reduced immunoglobulin levels, lowering the defense immune response and increased susceptibility to infections. Energy is also required to mount an appropriate immune response to infection. Furthermore, low muscle mass is an independent predictor of mortality in patients with cirrhosis and infections. Therefore, sarcopenia and
malnutrition predispose cirrhosis patients to infections and negatively impact the outcomes.\textsuperscript{150,151} Furthermore, sepsis may aggravate energy expenditure in patients with cirrhosis and further accelerate protein degradation.\textsuperscript{151,152} Therefore, a daily energy intake of 35 to 40 kcal/kg body weight and 1.2 to 1.5 g/kg protein is recommended. In addition, carbohydrate-containing late evening snacks may improve the nutritional status of patients with cirrhosis. It is also recommended to evaluate and supplement micronutrient deficiencies in cirrhosis patients.\textsuperscript{153} Further studies are required to assess the role of calorie intake in preventing infection.

**Key point:** sarcopenia and malnutrition can adversely affect outcomes of sepsis in patients with cirrhosis. A multidisciplinary approach is essential to prevent malnutrition and sarcopenia in this population.

### The Challenges of Bacterial Resistance

The epidemiology of infections has changed in recent years. The burden of MDROs and XDR (extensively drug resistant) organisms is rapidly increasing and is a serious global threat.\textsuperscript{154} The incidence of MDROs has increased from 20\% in 2012 to more than 30\% in recent years among patients with cirrhosis.\textsuperscript{4,14,106} MDROs are associated with an increased risk of organ failures, septic shock, and mortality.\textsuperscript{106,155} MDR infections are also associated with an increased health care and cost burden. Nosocomial and health care–associated infections are frequently caused by MDROs.\textsuperscript{106} Susceptible bacteria develop resistance to antibiotics by accumulating mutations or acquiring resistance genes that protect the cell against antibiotics.\textsuperscript{156} Antibiotic resistance genes (ARGs) can cause phenotypic resistance through enzymatic inactivation, target modification of the antibiotic, or by preventing intracellular accumulation through efflux pumps.\textsuperscript{154,156} The densely populated intestinal microbial ecosystem provides an opportunity for the horizontal transfer of resistance genes among microbes through conjugation and transduction.\textsuperscript{156} Enterococci, the widely prevalent commensal in patients with cirrhosis, can acquire, conserve, and disseminate resistance traits and thus increasing the risk of MDROs.\textsuperscript{157,158} Shotgun metagenomic sequencing (MGS) and functional metagenomics are excellent culture-independent methods to characterize the “human resistome (ARGs).” Antimicrobial resistance bioinformatic databases, such as the ResFinder, ARG-ANNOT, Resistance Determinants Database (RED-DB), National Center for Biotechnology Information (NCBI) Pathogen Detection Reference Gene catalog, and Comprehensive Antibiotic Resistance Database (CARD), curate information from the published literature into their database to support genotype sequence analysis.\textsuperscript{158,159} The knowledge and understanding of the resistome aids in assessing the burden and impact of antimicrobial resistance genes on outcomes in patients with cirrhosis.

**Key point:** antimicrobial resistance is a global threat. Novel techniques aid in the rapid diagnosis of infection and susceptibility patterns and may improve outcomes in patients with cirrhosis.

### Prevention of Multidrug Resistant Infections

The risk factors for MDROs include recurrent health care exposure, prolonged use of indwelling medical devices including vascular lines, urinary catheters, feeding tubes, endotracheal tubes, after prolonged hospitalization, colonization of MDROs in immunosuppressed patients, and lastly, the injudicious use of antibiotics.\textsuperscript{160} Patients with cirrhosis are immunosuppressed and are frequently exposed to health care settings due to the need for paracentesis, variceal ligation, hepatocellular carcinoma management, and optimization for liver transplantation. Moreover, patients with cirrhosis frequently require hospitalization.\textsuperscript{161} Antimicrobial stewardship is the need of the hour to prevent the exponential rise in incidence of MDRO infections. Antimicrobial stewardship not only includes judicious use of empirical antibiotics but also useful in timely deescalation and withdrawal.\textsuperscript{158} Restricting prolonged antibiotic use is also a part of antimicrobial stewardship; however, data on the optimum duration of therapy for infections other than SBP in cirrhosis is lacking.\textsuperscript{115} Cirrhosis patients, especially those planned for transplantation, should undergo nasal and rectal swab assessment for MDR organisms. Health care personnel involved in care of cirrhosis patients should also be evaluated for colonization of MDROs. Incorporating rapid detection methods (as discussed earlier) for the early identification of MDROs and isolating those who develop MDR infections is ideal. Education and training of health care personnel on universal precautions, including hand hygiene, avoiding unnecessary instrumentation, antimicrobial stewardship, and aseptic precautions, while performing paracentesis and variceal ligation, should be a part of hospital policy. Hospital-based policies aimed to monitor the incidence and local-susceptibility patterns and incorporating the changes in antibiotic policies are essential. National surveillance programs to understand the cause and prevalence of AMRs are needed. Novel nonantibiotic strategies, as discussed in this review, may also reduce the incidence of MDROs. Education, judicious use of antimicrobials, infection control precautions, frequent surveillance programs, and robust administrative support can contain MDR infections.

### Future Strategies and Novel Interventions

Immunonutrition is defined as the use of specific nutrients to modulate immune system activity.\textsuperscript{162} Omega-3 fatty acids (FAs) modulate prostaglandin (PG) metabolism and decrease triglycerides; furthermore, they can lower cholesterol levels at high doses and hence have antiinflammatory and anti-inflammatory properties.\textsuperscript{163} Omega-3 FAs inhibit the formation of omega-6 FA-derived proinflammatory eicosanoids such as PGE\textsubscript{2} and leukotriene B\textsubscript{4} (LTB\textsubscript{4}). Conversely, these omega-3 FAs can form potent antiinflammatory lipid mediators such as resolvins and protectins.\textsuperscript{164} Altogether, omega-3 FAs suppress the activity of nuclear factor kappa B and reduce the production of proinflammatory enzymes and cytokines, including cyclooxygenase-2, TNF-\textalpha, and IL-\textbeta.\textsuperscript{165} Recently, intravenous lipid emulsions were evaluated for the prevention of sepsis in patients with ACLF.\textsuperscript{45} Fish oil–based lipid emulsions suppressed endotoxin levels, IL-\textbeta, CRP, and prevented the rise
in TNF-α. Additionally, there was an increase in TLR expression with omega-3 FA lipid emulsions. Omega-6 FAs had a similar change but to a lesser extent. Compared with the control arm, omega-6 FAs and omega-3 FAs reduced sepsis by 53 and 86%, respectively. However, further studies are required to validate the role of these lipid emulsions as nutritional supplements and immunomodulators in patients with cirrhosis.

Fecal (or intestinal) microbiota transplantation (FMT) is a therapeutic modality for recurrent *C. difficile* infections. MDROs are common in patients with advanced cirrhosis due to frequent use of antibiotics and recurrent hospitalizations. Gut ARGs proportionately increases with the severity of liver disease and correlate with hospitalizations and mortality in patients with cirrhosis. Recently the effect of FMT on ARGs in cirrhosis was evaluated. Twenty patients treated with FMT were compared with 20 controls. Ten patients received 15 capsules (orally) of 4.125-g stool, and 10 received 5 days of broad-spectrum antibiotics followed by 90 mL of 27-g stool enema. There was a significant decrease in ARGs with FMT (more so with the oral route) compared with placebo. Further extensive, randomized controlled studies are required to evaluate the role of FMT in reducing the burden of MDROs and thus preventing sepsis.

Table 5  Mechanisms and role of drugs in prevention of infections in patients with cirrhosis

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Modality</th>
<th>Role</th>
<th>Dose</th>
<th>Beneficial effect</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NSBBs</td>
<td>Preprimary and primary prevention</td>
<td>Propranolol 20–80 per day or carvedilol at 3.125–25.0 mg based on tolerance</td>
<td>Reduces portal pressure; reduces intestinal permeability; reduces endotoxemia</td>
<td>Can reduce infections and improve survival. Disadvantages: risk of renal dysfunction and cardiac suppression in advanced cirrhosis patients</td>
</tr>
<tr>
<td>2</td>
<td>Albumin</td>
<td>Preprimary and primary prevention</td>
<td>40 g twice weekly for 2 weeks followed by 40 g weekly</td>
<td>Modulate Toll-like receptor (TLR) 4 expression; PGE2 mediated bacterial killing; Reverses plasma-mediated immune dysfunction</td>
<td>Definitive role in SBP treatment to prevent kidney injury and prolong mortality. Long-term therapy may prevent ACLF in decompensated cirrhosis patients. Limitations: doubtful role of albumin for prevention of non-SBP sepsis induced organ failures.</td>
</tr>
<tr>
<td>3</td>
<td>Antibiotics</td>
<td>Primary and secondary prevention</td>
<td>Norfloxacin 400 mg/day; Trimethoprim-sulfa-methoxazole; Ciprofloxacin 750 mg once weekly; Broad-spectrum antibiotics in severe sepsis (secondary prevention)</td>
<td>Rebalances gut dysbiosis; Inhibits gram-negative bacteria and endotoxemia</td>
<td>Prevent infection/SBP/renal injury in patients with gastrointestinal hemorrhage and in patients with low acetic fluid protein. Limitations: prophylactic antibiotics may increase the risk of MDROs.</td>
</tr>
<tr>
<td>4</td>
<td>Statins</td>
<td>Preprimary, primary, and secondary prevention</td>
<td>Simvastatin (20–40 mg/day) ± rifaximin (400 mg TID)</td>
<td>Anti-inflammatory, antiapoptotic, vasoprotective; Decrease the effect of sepsis-induced coagulopathy; Prevent endotoxin-induced intrahepatic endothelial dysfunction and hepatocyte death</td>
<td>Existing evidence support preprimary prophylaxis role. Further clinical studies required to confirm the role of simvastatin in preventing sepsis and the consequences of sepsis induced ACLF. Limitations: risk of rhabdomyolysis is high in decompensated cirrhosis patients.</td>
</tr>
<tr>
<td>5</td>
<td>G-CSF</td>
<td>Primary prevention</td>
<td>G-CSF (5 mg/kg/d) for 5 days and then every third day (12 total doses), along with subcutaneous darbeprinote (40 µg/week) for 4 weeks or EPO</td>
<td>Regeneration and improvement in neutrophil function by mobilization of CD 34+ cells from the bone marrow to the liver; Increased intrahepatic and circulating dendritic cells and decreased interferon (IFN)-γ secreting CD8 T cells</td>
<td>May be used as an experimental drug in early cirrhosis patients with low MELD score.</td>
</tr>
</tbody>
</table>

Abbreviations: ACLF, acute-on-chronic liver failure; EPO, erythropoietin; G-CSF, granulocyte colony-stimulating factor; MDROs, multidrug resistance organisms; MELD, model for end-stage liver disease; NSBBs, nonselective β-blockers; SBP, spontaneous bacterial peritonitis.
Recent studies show encouraging results in preventing alcohol-related liver disease through bacteriophage-mediated inhibition of cytotoxic *E. faecalis*. Phage therapy has been utilized in the prevention and treatment of HBV infection. Furthermore, bacteriophages have strong anti-inflammatory properties independent of antibacterial properties. Bacteriophages have been used in sepsis treatment. However, bacteriophages are strain specific and are limited by studies in preclinical models. Future studies should evaluate the role of phage therapy in preventing chronic liver disease (preprimary prevention) and treating sepsis in patients with cirrhosis (secondary prevention).

Sepsis is a common precipitant of ACLF through the LPS-TLR4 pathway. Recombinant alkaline phosphatase (recAP), developed from intestinal and placental alkaline phosphatase, dephosphorylates the LPS, reduces its activity, and reduces hepatic TLR4 expression. Thus, recAP may reduce the risk of organ dysfunction in sepsis-induced ACLF as part of secondary prevention. Resatorvid (TAK-242) is a small-molecule inhibitor of TLR4. Intravenous resatorvid may prevent organ dysfunction. Phase-II trials of this drug are underway (identifier: NCT04620148). Yak-001, an orally administered, nonabsorbable, synthetic microporous carbon has a high adsorptive capacity for bacterial products, LPS, and proinflammatory cytokines. Yak-001 was found to be safe and effective in reducing endotoxemia and inflammatory mediators in patients with decompensated cirrhosis in phase-II trials. Recently, obeticholic acid was shown to prevent BT in preclinical studies. While the preliminary data are very encouraging, the clinical utility of these drugs for the prevention of sepsis and consequent organ dysfunction requires further validation.

There is elevated COX-derived PGE2 in patients with acute hepatic decompensation; the COX inhibitor indomethacin helps restore macrophage immune function and improve survival in the mouse model of liver injury and thus may prevent infection. However, preexisting platelet dysfunction and risk of renal failure prohibit us from exploring these drugs in patients with cirrhosis. Lastly, DIALIVE, a novel liver dialysis device that replaces dysfunctional albumin and removes pathogen and damage-associated molecular patterns (DAMPs), has been shown to improve outcomes in patients with ACLF. Further studies should evaluate the role of such novel devices in the prevention of organ failures in sepsis-induced ACLF.

**Key point:** many therapeutic and preventive strategies are evolving. Further multicenter research involving novel interventions may improve the outcomes of critically ill cirrhosis patients and reduce the global mortality attributed to liver diseases.

**Conclusion**

Infections and consequent sepsis remain a challenging clinical conundrum in the management of patients with cirrhosis. Due to ill-defined diagnostic criteria, lack of absolute biomarker cut-offs, and overlap with secondary organ failures, prevention, early diagnosis, and timely therapy remain a challenge. Yet, there have been major advances in understanding the frequency, consequences, and therapy of infections and sepsis in cirrhosis. It is crucial to prevent sepsis in patients with cirrhosis at primary and secondary levels with several advanced measures (Table 5). The progression of sepsis-induced liver failure may be mitigated with early identification and appropriate management. In addition, universal precautions are required at all stages to avoid infections, secondary sepsis, and organ failures in patients with cirrhosis. Despite the availability of multiple interventions, successful management of patients with cirrhosis and sepsis remains a challenge in 2022 in view of the need for advanced organ support, scarcity of donors for transplantation, and COVID-19-related interruptions in therapy.

**Lay Summary**

Infections in patients with cirrhosis significantly contribute to morbidity and mortality. Infections in cirrhosis frequently lead to organ failures. Therefore, preventing infections may improve the outcomes of patients with cirrhosis by preventing downstream complications. In this article, we discussed several measures, including antibiotic and nonantibiotic-based interventions, to prevent infections in cirrhosis and improve outcomes.

**Abbreviations**

ACLF, acute-on-chronic liver failure; AKI, acute kidney injury; ARG, antibiotic resistance gene; BT, bacterial infection; CLIF-SOFA, chronic liver failure-sequential organ failure assessment; CLP, cecal ligation and puncture; COVID-19, novel coronavirus disease 2019; CRP, C-reactive protein; FA, fatty acid; FMT, fecal microbiota transplantation; G-CSF, granulocyte-colony stimulating factor; GNB, gram-negative bacilli; GPC, gram-positive cocci; HAS, human albumin solution; HO-1, heme oxygenase-1; ICU, intensive care unit; IFN, interferon; iNOS, endotoxin-induced nitric oxide synthase; LPS, lipopolysaccharide; LTBI, leukotriene B4; MDRO, multi-drug resistant organism; MR-proADM, mid-regional pro-adrenomedullin; NAFLD, nonalcoholic fatty liver disease; NASH, nonalcoholic steatohepatitis; NLR, neutrophil-to-lymphocyte ratio; NSBB, Non-selective β-blocker; PCT, procalcitonin; PG, prostaglandin; PGE2, prostaglandin E2; PPI, proton pump inhibitor; qSOFA, quick sequential organ failure assessment; recAP, recombinant alkaline phosphatase; SBP, spontaneous bacterial peritonitis; SID, selective intestinal decontamination; SIRS, systemic inflammatory response syndrome; SOFA, sequential organ failure assessment; SSTI, skin and soft tissue infection; UTI, urinary tract infection; TLR, toll-like receptor; TNF, tumor necrosis factor; TREM-1, triggering receptor expressed on myeloid cells-1; WCC, white cell count.

**Authors’ Contributions**

K.R.R. and N.R.P. developed the study concept; A.V.K., K.K., and M.P. wrote the initial draft; A.V.K. and M.P. prepared the figures; J.P.A., M.S., and K.K. prepared the tables; J.P.A., D.N.R., N.R.P., and K.R.R. critically assessed the draft. K.R.R. and A.V.K. are the guarantors of the article. All members approved the final manuscript.

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Conflit d'intérêt None declared.

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