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(REVIEW ARTICLE)

Quality assurance metrics and lean management interventions for reducing errors in high-volume hospital blood culture processing

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Abstract

Bloodstream infections remain a major cause of morbidity and mortality worldwide with blood cultures serving as the diagnostic gold standard. However, in high-volume hospital settings, the reliability of blood culture results is frequently compromised by pre-analytical and analytical errors including blood culture contamination. This narrative review synthesizes evidence published between 2020 and 2025 on quality assurance (QA) metrics and Lean management interventions aimed at reducing errors in high-throughput blood culture processing. Core QA indicators like contamination rates, blood volume adequacy and utilization rates are examined as foundational tools for monitoring performance and guiding improvement. The integration of these approaches creates a feedback loop whereby data-driven measurement informs systematic intervention and improvement outcomes against established benchmarks. Emerging technologies such as blood culture diversion devices, automated laboratory systems, and standardized collection kits, demonstrate promise in augmenting these efforts. Multimodal interventions combining standardized protocols with targeted staff training consistently reduced contamination rates across diverse clinical settings. Inadequate blood volume collection with mean volumes as low as 4.5 mL in some hematology wards significantly compromise diagnostic sensitivity. The review highlights the value of integrating QA metrics with Lean methodologies that support sustained quality improvement. Persistent gaps remain in long-term sustainability, economic evaluation, human factors research and standardization across healthcare systems. Addressing these gaps is essential to improving diagnostic accuracy, antimicrobial stewardship and healthcare efficiency.

Keywords: Turnaround time; Blood culture contamination; Lean Six Sigma; Indicator; Optimization

1. Introduction

One of the most critical and ongoing challenge in global healthcare is Bloodstream infections (BSIs) which demands rapid and accurate diagnosis to guide timely and effective antimicrobial therapy in ill patients (Dai et al., 2024). Blood cultures (BCs) are universally recognized as the gold standard for detecting BSIs, providing essential insights into causative pathogens and their antimicrobial susceptibility profiles (Fernandes et al., 2025; Aravind et al., 2025). The diagnostic cornerstone is vital for improving patient outcomes, reducing morbidity and mortality, and supporting judicious antimicrobial stewardship programs (Kusnik et al., 2025; Bunn et al., 2025).

Despite their indispensable role, the diagnostic utility of BCs is frequently hampered by significant pre-analytical and analytical errors that cause substantial clinical and economic repercussions (Almotairi et al., 2025). A prevalent issue is blood culture contamination (BCC), where microorganisms from the patient's skin or the environment are inadvertently introduced into the sample during collection (Azem and Ransom, 2022; Sautter et al., 2024; Kusnik et al., 2025). Rates of BCC typically range from 1% to over 10% of all BC results in various clinical settings. This considerably exceed the recommended benchmark of less than 3% set by leading professional bodies such as the American Society

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for Microbiology and the Clinical Laboratory Standards Institute (Sautter et al., 2024; Badejogbin et al., 2025; Willingham et al., 2026; Aldiba et al., 2023; Manzoor and Turbett, 2025). False-positive BC results due to contamination impose a significant burden on healthcare systems. They frequently lead to unnecessary antimicrobial treatments, contributing to the development of antimicrobial resistance, increase drug-related adverse events, and escalate healthcare costs (Fatima et al., 2023; Sautter et al., 2024; Kusnik et al., 2025). The economic impact of BCC can be severe, sometimes exceeding $100,000 per case depending on the scope of analysis. This is primarily due to prolonged hospital stays, additional diagnostic procedures, and inappropriate antimicrobial use (Otter et al., 2026;). Furthermore, the increased incidence of BCC has been observed during and after public health crises, such as the COVID-19 pandemic, potentially exacerbated by factors like the deployment of less experienced staff for sample collection (Nizam et al., 2025).

Another critical error impacting diagnostic accuracy is the collection of insufficient blood volume (Bunn and Cornish, 2025). Standard guidelines recommend collecting 8–10 mL of blood per BC bottle to maximize the detection of pathogens, as lower volumes can significantly reduce the sensitivity of the test (Tseng et al., 2023; Kusnik et al., 2025; Yuen et al., 2026). Suboptimal blood volumes often result in false-negative culture results delaying the initiation of appropriate treatment, prolonging patient illness and increasing the risk of adverse clinical outcomes (Bunn and Cornish, 2025). Studies have highlighted that achieving adequate blood culture volumes remains a persistent challenge in practice. For instance, some hematology wards reported a baseline mean blood count volume (BCV) of 4.5 mL, well below the recommended range (Yuen et al., 2026). These pre-analytical errors including patient misidentification, improper labeling and hemolysis account for a majority of laboratory mistakes and underscore the vulnerability of the initial stages of the BC process (Almotairi et al., 2025).

The imperative for optimizing current practices in high-volume hospital settings is thus undeniable. The high throughput of samples in these environments amplifies the potential for errors and their downstream consequences. Rigorous quality assurance (QA) and process optimization are essential to minimize errors, enhance diagnostic reliability, improve patient safety, and support effective antimicrobial stewardship (Kusnik et al., 2025; Dai et al., 2024). This includes the continuous monitoring of key performance indicators (KPIs) and the implementation of structured improvement methodologies (Moschandreou and Grouzi, 2025).

This review aims to interpret recent advancements, emerging trends, and critical knowledge gaps (2020 to 2025) concerning quality assurance metrics and lean management interventions specifically designed to reduce errors in high-volume hospital blood culture processing. By synthesizing evidence from peer-reviewed literature, this review provides a synthetic and expert-driven perspective to inform future research and practical implementation strategies, ultimately contributing to more reliable BSI diagnostics and improved patient care.

1.1. Quality Assurance Metrics

Quality assurance (QA) metrics are fundamental to identifying, monitoring, and driving continuous improvements in blood culture processing. It is a critical quality check for accurate diagnosis of bloodstream infections and effective antimicrobial stewardship (Dai et al., 2024). The evolving landscape of healthcare emphasizes the need for rigorous QA to enhance patient safety and optimize resource utilization, particularly in high-volume settings.

1.2. Core Quality Indicators in Blood Culture Processing

Blood Culture Contamination (BCC) Rate: The BCC rate is a primary quality indicator with benchmarks consistently set below 3% by organizations such as the American Society for Microbiology and the Clinical Laboratory Standards Institute (Badejogbin et al., 2025; Kumar et al., 2025). Achieving and maintaining this benchmark is a persistent challenge in clinical practice (Manzoor and Turbett, 2025; Otter et al., 2026). Institutions are increasingly focusing on standardized surveillance and reporting methods to accurately track BCC rates and identify areas for intervention. This trend towards universal standards is crucial for inter-institutional comparisons and collaborative improvement efforts (Manzoor and Turbett, 2025). Factors contributing to BCC often include inadequate staff training, suboptimal skin antisepsis, and other issues during the pre-analytical phase (Fernandes et al., 2025; Almotairi et sl., 2025). Blood culture diversion devices (BCDDs) represent a promising strategy to reduce BCC, showcasing significant impact on contamination rates and patient safety (Otter et al., 2026).

Blood Volume Adequacy: The volume of blood collected for culture is a critical determinant of diagnostic yield (Azem and Ransom, 2022; Krapp et al., 2022). Guidelines recommend collecting 8–10 mL per blood culture bottle to maximize pathogen detection. Suboptimal volumes (mean BCV of 4.5 mL) significantly reduce the sensitivity of the test, potentially leading to false-negative results and delayed appropriate therapy (Yuen et al., 2026). Monitoring actual collected volumes against these recommended guidelines is essential and tools like Plan-Do-Check-Act (PDCA) cycles can be

effectively employed to improve collection practices (Fernandes et al., 2025). Despite clear recommendations, achieving adequate blood culture volumes remains a persistent challenge in practice. For example, some hematology wards have reported mean blood culture volumes as low as 4.5 mL, considerably less than the recommended range (Yuen et al., 2026).

Positivity Rate and Clinical Relevance: Interpreting the blood culture positivity rate requires careful consideration in conjunction with contamination rates to avoid misdiagnosis. A high positivity rate coupled with a high BCC rate might suggest widespread contamination rather than a true increase in bloodstream infections, leading to inappropriate clinical decisions and unnecessary antibiotic use. The clinical relevance of positive cultures must be meticulously evaluated especially when common skin commensals are identified, necessitating differentiation between true infection and contaminant (Azem and Ransom, 2022).

Turnaround Time (TAT): The turnaround time for blood cultures encompasses various components, from sample collection to the final antimicrobial susceptibility testing (AST) report (Qin et al., 2025; Liu et al., 2024). TAT critically impacts patient outcomes and antimicrobial stewardship by influencing the timeliness of appropriate antibiotic administration and de-escalation. Prolonged TAT can delay crucial treatment decisions, leading to increased morbidity and mortality. Efforts to reduce TAT often focus on workflow optimization, automation in microbiology laboratories, and rapid diagnostic technologies (Dai et al., 2024; Trigueiro et al., 2024). For example, the median TAT from specimen collection to AST reports varied from 2.35 to 3.25 days across different Chinese teaching hospitals, indicating areas for improvement (Liu et al., 2024).

Blood Culture Utilization Rate: Tracking the blood culture utilization rate is paramount for effective diagnostic stewardship programs (Marquez and Palazzi, 2022). Excessive or inappropriate blood culture testing, particularly in patients with a low probability of bloodstream infection, contributes to unnecessary costs, increased workload and a higher likelihood of false-positive results. Diagnostic stewardship aims to optimize BC use by ensuring cultures are obtained only when diagnostically valuable, reducing inappropriate testing and associated negative consequences (Badejogbin et al., 2025; Marquez and Palazzi, 2022). Interventions combining education and restriction in intensive care units have demonstrated effectiveness in reducing utilization rates without compromising patient safety (Wang et al., 2023; Rodriguez et al., 2024). The figure below illustrates the impact of such an intervention on BC utilization in an intensive care unit.

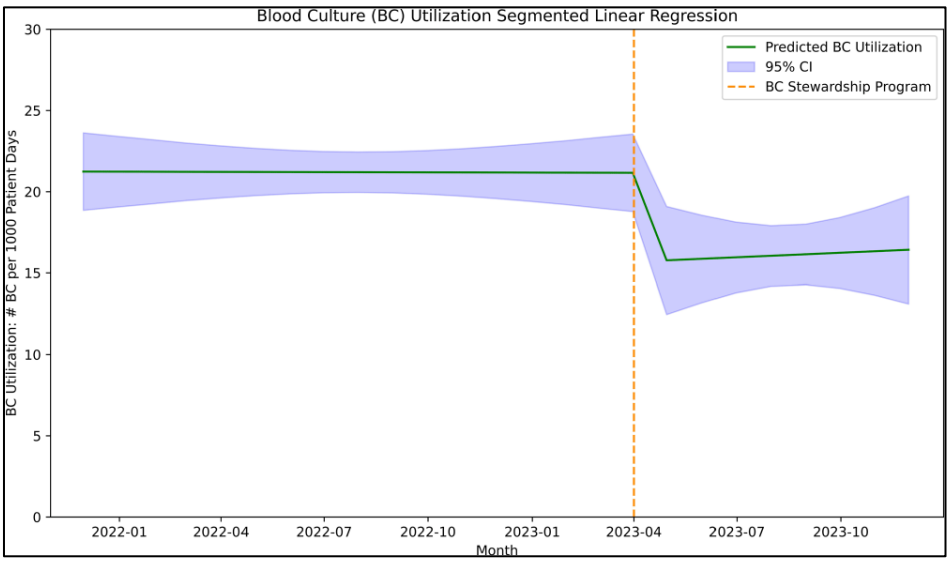

Figure 1 Blood Culture Utilization Trend (Rodriguez et al., 2024)

Harmonization of Quality Indicators: There is a discernible trend towards developing universal benchmarks and standardized surveillance methods for blood culture quality indicators across different laboratories and healthcare systems. Such harmonization facilitates benchmarking, allows for more accurate comparisons of performance, and promotes the widespread adoption of best practices for reducing errors and improving diagnostic reliability **3**. Standardized processes for monitoring and reporting as advocated by organizations like the American Society for Microbiology are crucial for this collective improvement (Manzoor and Turbett, 2025).

Leveraging Data for Continuous Monitoring: The increasing use of Key Performance Indicators (KPIs) and systematic quality management reviews (QMRs) is instrumental in identifying system weaknesses and driving continuous improvement initiatives in blood culture processing. By systematically collecting and analyzing data related to BCC rates, blood volume adequacy, TAT, and utilization rates, healthcare facilities can pinpoint specific areas requiring intervention. This data-driven approach often integrated into Lean management principles enables targeted strategies to enhance the overall quality and efficiency of blood culture processing which ultimately benefit patient care (Moschandreou & Grouzi, 2025).

2. Lean Management Interventions: Streamlining Processes for Error Reduction

Lean management, a philosophy derived from the Toyota production system, focuses on maximizing value by eliminating waste and improving operational efficiency (Joshi et al., 2025; Cherie et al., 2024). Its application in healthcare, particularly in high-volume laboratory settings, has demonstrated significant potential for error reduction and improved patient outcomes (Sancho et al., 2023; Trigueiro et al., 2024). The DMAIC (Define, Measure, Analyze, Improve, Control) framework of Lean Six Sigma provides a structured, data-driven methodology for systematically solving problems and improving lab processes (Zhao et al., 2024). This section focuses on practical interventions guided by lean principles that are crucial for minimizing errors and optimizing processes in high-volume blood culture (BC) processing.

2.1. Standardization of Protocols and Training

Standard Operating Procedures (SOPs): Implementing clear, standardized operating procedures (SOPs) for BC collection and processing is fundamental to reducing variability and errors (Wang et al., 2026; Fernandes et al., 2025). Training of phlebotomists and nurses in proper blood sampling techniques, including skin antisepsis and avoiding contamination, has proven effective in reducing BCC rates (Adnan et al., 2024; Kusnik et al., 2025; Ruiz et al., 2024). Multimodal interventions, such as those based on the "Blood Culture Train" (BCT) framework, which incorporates CLSI M47-A compliant workflows, blockchain-enabled traceability and VR-based training can enhance compliance and diagnostic yield (Wang et al., 2026).

Training and Competency: Targeted education and training for healthcare personnel involved in blood collection, particularly phlebotomists and nurses are critical for minimizing errors. Innovative approaches such as simulation-based training or virtual reality (VR)-based training can significantly improve technique and reduce contamination rates (Nizam et al., 2025). Multimodal interventions, combining process improvements with behavioral changes have shown promise in enhancing staff competency and reducing errors (Fatima et al., 2023).

2.2. Process Optimization and Automation

Process Mapping, Value Stream Analysis and Laboratory Automation: Techniques like process mapping and value stream analysis are instrumental in visualizing the entire blood culture workflow. By identifying bottlenecks, redundant steps and areas of waste, these analyses enable healthcare facilities to optimize processes, reduce errors, and decrease turnaround times (TAT) (Cherie et al., 2024; Qin et al., 2025). The integration of automation in microbiology laboratories, through systems like WASPLab or VITEK MS, offers substantial benefits (Trigueiro et al., 2024). Automation reduces manual handling, thereby minimizing human error, increasing efficiency, and significantly shortening TAT for pathogen identification and susceptibility testing (Dai et al., 2024; Fernandes et al., 2025).

3. Diagnostic Stewardship Programs

Rationale and Implementation: Diagnostic stewardship programs are essential for addressing the "silent error" of blood culture overutilization. These programs aim to reduce unnecessary BC orders and improve the appropriateness of testing by leveraging evidence-based algorithms, provider education, and, in some cases, order restrictions. By optimizing BC utilization, these programs mitigate associated costs, reduce false positives, and support antimicrobial stewardship efforts (Wang et al., 2023; Rodriguez et al., 2024).

Adaptation to Supply Chain Challenges: Diagnostic stewardship also plays a crucial role in managing resource limitations, such as shortages of blood culture bottles (Aravind et al., 2025). By ensuring that cultures are ordered only when clinically indicated, these programs help conserve critical supplies and maintain diagnostic capability during periods of scarcity.

3.1. Technological Innovations

Blood Culture Diversion Devices (BCDDs): Blood culture diversion devices (BCDDs) have emerged as a promising technological innovation to reduce BCC. These devices divert the initial aliquot of blood, which is most likely to contain skin contaminants, away from the culture bottles, thereby significantly lowering contamination rates. Ongoing evaluations continue to assess their impact on BCC and overall cost-effectiveness (Otter et al., 2026).

Standardized Collection Kits: The use of pre-packaged, standardized collection kits helps to streamline the blood culture collection process and ensure adherence to best practices. By including all necessary components and clear instructions, these kits reduce variability in technique and minimize the risk of contamination during collection (Willingham et al., 2026).

3.2. Emerging Trends and Future Directions

This section identifies forward-looking aspects and nascent developments that are poised to transform blood culture processing, quality assurance, and error reduction strategies.

3.3. Advanced Analytics and Artificial Intelligence (AI)

The future of blood culture processing will likely see an increased role for artificial intelligence (AI) and machine learning (ML). These technologies hold significant potential in predicting blood culture contamination (BCC) risk to facilitate optimize laboratory workflows and enable real-time monitoring of various quality indicators. AI algorithms could analyze vast datasets, including patient demographics, clinical history and laboratory results to identify patterns indicative of potential contamination before or during sample collection. This proactive identification could allow for immediate interventions, thereby reducing false-positive rates and their associated clinical and economic burdens (Dai et al., 2024). Furthermore, AI could optimize resource allocation within laboratories, streamline instrument utilization, and enhance the efficiency of diagnostic pathways, ultimately reducing turnaround times (TAT) and improving patient care.

3.4. Integration of Molecular Diagnostics

Rapid molecular techniques are increasingly complementing traditional blood cultures, significantly expediting pathogen identification and antimicrobial susceptibility testing (AST) These advanced methods which include polymerase chain reaction (PCR) and next-generation sequencing (NGS) can detect microbial DNA or RNA directly from blood samples that often yield results hours or days faster than conventional culture-based methods. The acceleration in diagnosis allows for earlier initiation of targeted antimicrobial therapy crucial for improving outcomes in patients with bloodstream infections and reducing the selective pressure for antimicrobial resistance (Dai et al., 2024). The integration of molecular diagnostics while requiring initial investment and specialized expertise, represents a major step towards personalized and timely infection management.

3.5. Personalized Diagnostic Stewardship

A nascent development is the potential for personalized diagnostic stewardship, which would involve patient-specific risk assessments to guide blood culture ordering and more effectively interpret results. This approach moves beyond generalized guidelines to consider individual patient factors, such as comorbidities, recent antibiotic exposure, and localized epidemiology, to determine the likelihood of true bloodstream infection versus contamination or colonization. By tailoring blood culture practices to individual patient profiles, clinicians can optimize test utilization, reduce over-ordering, minimize false positives, and ensure that diagnostic resources are deployed most effectively (Otter et al., 2026). This personalized strategy aims to enhance diagnostic accuracy while concurrently supporting antimicrobial stewardship efforts.

Interdisciplinary Collaboration and System-Wide Approaches: There is a growing emphasis on interdisciplinary collaboration and integrated, system-wide approaches to improving blood culture quality. Effective error reduction and quality assurance in blood culture processing necessitate active involvement from a diverse range of healthcare professionals, including clinicians (physicians, nurses), microbiologists, laboratory technicians, infection control specialists, and quality improvement (QI) experts. Multidisciplinary teams can collaboratively develop and implement standardized protocols, conduct targeted training, and continuously monitor key performance indicators. Such integrated strategies ensure that improvements are holistic, addressing issues across the entire patient journey from specimen collection to result interpretation and subsequent therapeutic decisions (Wang et al., 2023). This collaborative framework fosters a culture of safety and continuous improvement within healthcare institutions.

3.6. Environmental and Sustainability Considerations

Beyond clinical and economic outcomes, future directions in blood culture processing will increasingly incorporate environmental and sustainability considerations. Optimizing blood culture processes through lean management interventions naturally leads to waste reduction and more efficient resource utilization. By minimizing unnecessary blood cultures, reducing contamination, and streamlining workflows, healthcare facilities can decrease the consumption of disposables, reagents, and energy. This focus on sustainability aligns with broader healthcare initiatives to reduce environmental impact and conserve resources, contributing to both ecological responsibility and operational efficiency within laboratories (Otter et al., 2026).

3.7. Knowledge Gaps and Research Imperatives

Although significant advancements have been made in identifying and mitigating errors in high-volume hospital blood culture processing, several critical knowledge gaps and areas for future research remain to ensure sustained improvements and broader applicability. Addressing these imperatives is essential for enhancing patient care, optimizing resource utilization, and advancing the field of diagnostic stewardship.

3.8. Long-term Efficacy and Sustainability of Interventions

Many quality improvement initiatives for reducing blood culture contamination (BCC) demonstrate short-term success, yet there is a limited number of research evaluating the sustained impact and long-term scalability of these interventions. For instance, while process improvement studies show initial reductions in BCC rates through focused efforts, the durability of these improvements over extended periods and their transferability to other hospital units or even different healthcare systems often remain underexplored (Fatima et al., 2023; Fernandes et al., 2025). Future research should focus on longitudinal studies to track BCC rates and other quality metrics over several years, assessing the factors that contribute to the persistence or decline of initial gains. This includes investigating how changes in staff, leadership and hospital policies affect the long-term effectiveness of implemented strategies.

4. Comprehensive Economic Evaluations

A significant gap exists in robust cost-benefit analyses for newer technologies and integrated Lean management programs aimed at reducing blood culture errors (Acker and Poonawala, 2026; Paur et al., 2019). For instance, while blood culture contamination is known to incur an average cost of $6,000 per contaminated sample due to unnecessary tests and prolonged hospital stays, detailed economic evaluations comparing the upfront investment in specific interventions (e.g., blood culture diversion devices (BCDDs), advanced training programs, or comprehensive diagnostic stewardship initiatives) against their long-term cost savings are often lacking (Acker and Poonawala, 2026; Paur et al., 2019). Studies should quantify not only direct costs (e.g., antibiotic usage, extended hospitalization, additional diagnostic tests) but also indirect costs (e.g., increased laboratory workload, patient discomfort, potential for antimicrobial resistance) associated with blood culture errors versus the implementation and maintenance costs of various interventions. This will provide healthcare administrators with stronger evidence for resource allocation and implementation decisions.

4.1. Impact of Human Factors and Training on Variability

Further investigation is needed into how human factors, such as staff turnover, varying experience levels, and the effectiveness of continuous education, impact BCC rates, particularly in diverse healthcare contexts (Gupta and Codd, 2020). The pre-analytical phase, which is heavily reliant on human interaction, accounts for a substantial majority of laboratory errors, potentially up to 70%. Therefore, understanding the nuances of staff competency, adherence to standardized operating procedures (SOPs), and the psychological factors influencing compliance is crucial (Fernandes et al., 2025). Research should explore different training methodologies (e.g., simulation-based training, blended learning, just-in-time education) and their long-term effectiveness in maintaining low BCC rates amidst staff fluctuations. Qualitative studies could also shed light on barriers to adherence and how to foster a stronger safety culture among phlebotomists and nurses.

4.2. Standardization Across Diverse Healthcare Systems

The generalizability of interventions aimed at reducing blood culture errors needs to be rigorously tested in low-resource settings and different cultural contexts (Manzoor and Turbett, 2025). While national benchmarks for BCC rates typically fall between 2% and 3%, actual rates can vary widely, sometimes exceeding 10% in certain facilities (Paur et al., 20219; Sautter et al., 2024). There is currently no universally standardized process to monitor and report BCC rates by individual healthcare facilities in the United States, further complicating comparisons and widespread

implementation of successful strategies (Manzoor and Turbett, 2025). Future research should focus on developing adaptable quality improvement frameworks that account for variations in infrastructure, staffing levels, patient populations, and cultural practices. This includes identifying core components of successful interventions that can be tailored to local needs without compromising efficacy, thus promoting a universal standard for blood culture quality.

4.3. Development of Novel Technologies for Pre-analytical Phase

There is an ongoing need for research into novel technologies that can inherently minimize contamination risk at the point of blood collection, particularly during the critical pre-analytical phase (Doern et al., 2019; Bunn et al., 2025). While existing technologies like blood culture diversion devices have shown promise in reducing BCC, further innovation is required to address remaining challenges and improve user-friendliness and cost-effectiveness. This includes exploring advancements in automated blood collection systems, intelligent skin antisepsis verification, and real-time feedback mechanisms for phlebotomists. The goal is to develop technologies that either automate critical steps or provide immediate corrective feedback to reduce human variability and enhance the sterility of blood sample collection, thereby reducing false-positive results and improving diagnostic accuracy for bloodstream infections.

5. Conclusion

Ensuring the accuracy and reliability of blood culture processing in high-volume hospital settings remains a persistent challenge that requires an integrated and systematic approach. This review demonstrates that the combined use of Quality Assurance (QA) metrics and Lean management interventions is essential for reducing errors and achieving sustained improvements in blood culture quality. Blood culture contamination (BCC) and inadequate blood volume continue to be major contributors to diagnostic errors, leading to inappropriate antibiotic use, prolonged hospitalization, and increased healthcare costs. The pre-analytical phase largely dependent on human performance accounts for the majority of these errors, underscoring the limitations of fragmented or reactive quality improvement efforts. In contrast, a comprehensive strategy that integrates robust QA metrics with Lean methodologies offers a more effective and sustainable solution. QA metrics such as BCC rates, blood volume adequacy, positivity rates, and turnaround time serve as critical tools for identifying performance gaps and monitoring improvement. Continuous surveillance using key performance indicators enables data-driven decision-making and targeted interventions. Lean management principles complement these metrics by providing structured methods to address root causes through standardization, staff training, process mapping, and workflow optimization. Diagnostic stewardship initiatives further reduce unnecessary blood cultures and associated risks, while technological solutions such as blood culture diversion devices and standardized collection kits help mitigate contamination at the point of collection. The synergy between QA metrics and Lean interventions creates a continuous feedback loop in which measurement informs action and intervention drives measurable improvement. However, important gaps remain, including the long-term sustainability of interventions, economic evaluations, variability in human factors, and standardization across healthcare systems. Overall, sustained improvement in blood culture quality requires a firm commitment to both quantitative monitoring and systematic process improvement. Integrating QA metrics with Lean management is imperative for enhancing diagnostic accuracy, strengthening antimicrobial stewardship, reducing costs, and ultimately improving patient safety and outcomes.

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