



Critical Values in Clinical Laboratories, an Underutilized Life-Saving Laboratory Results: A Narrative Review

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Abstract

Review Article

Background: Critical values are life-threatening laboratory results requiring immediate clinical intervention. While high-income countries have heavily automated the notification process via Laboratory Information Systems (LIS) and middleware algorithms, low- and middle-income countries (LMICs) often rely on manual, error-prone workflows.

Objective: To review current practices, challenges, and strategies for critical value notification; to compare proprietary versus open-source LIS notification systems for LMIC settings; and to propose a standardized closed-loop algorithm to improve patient safety.

Methods: A narrative review of current guidelines (CLSI, CAP, Joint Commission and ISO 15189:2022), LIS technologies, and implementation barriers was conducted. We specifically examine the challenges of power instability, software costs, and personnel shortages in Africa.

Results: Automation reduces notification time from an average of >40 minutes (manual) to <6 minutes (fully automated LIS). However, successful implementation requires overcoming significant infrastructural barriers. Case studies from Nigeria and Kenya demonstrate the viability of hybrid models, such as SMS-based automated alerts and open-source LIS, to bridge this gap.

Conclusion: Closed-loop communication for critical values is essential for patient safety. Achieving it requires investment in locally adaptable technologies, structured governance, and continuous personnel training, particularly in resource-limited settings.

Keywords: Critical Values; Laboratory Information System; Patient Safety; SMS Alert; Open-source LIS; Notification Algorithm; LMIC.

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INTRODUCTION

Critical values represent one of the most vital post-analytical components of laboratory medicine. Defined as laboratory results indicating a pathophysiologic state so extreme that it places the patient at immediate risk of morbidity or mortality unless urgent action is taken.[1] The concept was first introduced by Dr. George Lundberg in 1972 as "panic values".[2] Over the past five decades, this concept has evolved from a novel idea into a fundamental patient safety mandate across clinical laboratories worldwide.

Historically, the clinical laboratory's primary responsibility was heavily focused on analytical accuracy, ensuring the correct result was generated by the analyzer. Today, the scope of laboratory responsibility extends deeply into the pre-analytical and post-analytical phases. The post-analytical phase, specifically the timely and accurate notification of critical results to the licensed caregiver, is now recognized as a high-risk area for medical errors.[3] Failure in this communication chain remains a leading cause of sentinel events reported to international accrediting bodies, frequently resulting in delayed treatments, prolonged hospital stays, and preventable patient deaths.[4]

Globally, the rise of automation, sophisticated LIS, and intelligent middleware has radically shortened notification times and improved documentation compliance.[5] However, the adoption of these technologies is alarmingly uneven. In high-income countries (HICs), over 80% of tertiary hospitals utilize semi-automated or fully automated electronic alerts integrated directly with Electronic Health Records (EHR).[6] Conversely, in Sub-Saharan Africa (SSA) and other resource-limited settings, the vast majority of laboratories still rely on manual transcription and phone calls. This reliance on manual processes is driven by prohibitive software costs, severe infrastructure gaps, and a shortage of health informatics professionals.[7]

This review critically examines current practices, international regulatory frameworks, technological

advancements, and specific implementation challenges. By integrating real-world case studies and comparative analyses, it outlines actionable strategies to improve patient safety, with a particular focus on bridging the gap between resource-rich and resource-limited healthcare settings.

REGULATORY FRAMEWORK AND DEFINITIONS

Despite the universal recognition of critical values, there is no single, internationally mandated list of tests or critical limits. Regulatory and accreditation bodies deliberately require each laboratory to establish its own tailored list, formulated through rigorous consultation with clinical staff, taking into account the institution's specific patient population (e.g., pediatric vs. oncology vs. general adult).[8]

Key International Guidelines:

CLSI GP47-A: The Clinical and Laboratory Standards Institute provides the gold standard for policy development. It mandates a written policy that explicitly covers what constitutes a critical value, exactly who is authorized to receive the notification, the acceptable timeframe for reporting, mandatory documentation requirements, and a structured escalation procedure (a 'chain of command') to be activated if the primary clinician is unreachable.[9]

The Joint Commission (TJC) NPSG.02.03.01: As part of its National Patient Safety Goals, TJC strictly mandates closed-loop communication. Laboratories must use a "read-back" process where the receiver writes down and reads back the patient details and result to confirm accuracy. Furthermore, documentation must seamlessly capture the date, exact time, test name, result, the full name of the person notified, and the identity of the person reporting.[10]

CAP Laboratory Accreditation Program: The College of American Pathologists requires laboratories to achieve a median notification time of

<30 minutes from the time the result is analytically verified. It also requires an annual multidisciplinary review of the critical value list to ensure continued clinical relevance.[11]

ISO 15189:2022: The International Organization for Standardization emphasizes risk management and mandates that laboratories immediately notify the user of results falling within established critical intervals, ensuring clinical action can be taken without delay.[12]

Furthermore, modern laboratories must define "delta critical" or rate-of-change critical. A delta critical occurs when a patient's result changes drastically from a previous baseline over a short period, representing a life-threatening physiological shift, even if both the old and new values fall strictly within the normal reference range (e.g., a rapid drop in hemoglobin from 140 g/L to 90 g/L following surgery).[13] Establishing these parameters requires sophisticated LIS logic.

CURRENT PRACTICES IN NOTIFICATION

Notification methodologies today fall along a broad spectrum, ranging from completely manual workflows to AI-driven automated dispatch algorithms.

Manual Call-back:

Manual notification remains the prevailing standard in most LMICs and smaller rural clinics globally. Upon verifying a critical result on the analyzer, the laboratory scientist manually searches for the physician's or ward's phone number, places a call, verbally relays the patient ID and result, waits for a read-back, and handwrites the interaction in a physical logbook.[7] While advantageous due to its near-zero software cost, it is plagued by inefficiencies. Disadvantages include severe delays during off-hours, non-updated contact directories, and poor documentation compliance.[14] Studies conducted in Nigerian tertiary centers revealed an average notification time of 42 to 55 minutes using

this method, falling well outside international safety benchmarks.[7]

Semi-Automated LIS Alerts:

The implementation of a modern Laboratory Information System allows for rule-based flagging. When a result exceeds the predefined critical limit, the LIS visually flags the result on the screen (often in flashing red) and automatically generates an SMS, a pager alert, or an EHR inbox message to the responsible clinician.[15] The clinician must then acknowledge the alert electronically. This drastically reduces human transcription error and guarantees a digital audit trail. Genzen et al. reported a dramatic reduction in median notification time from 28 minutes down to just 6 minutes following the implementation of LIS-driven alerting mechanisms.[16]

Fully Automated Middleware and Artificial Intelligence:

The frontier of critical value reporting lies in intelligent middleware and AI. Middleware can execute complex, multi-variable logic before triggering an alert. For example, it can suppress false-positive critical potassium alerts if it detects a high hemolysis index in the sample, prompting a redraw rather than waking a physician at 3 am. [17] AI algorithms are currently being trained to contextualize results against the patient's EHR data. An AI system might flag a critical creatinine in an acute setting for immediate escalation, while recognizing the same value in a chronic dialysis outpatient as expected, thereby extending the notification window and severely reducing "alert fatigue" among busy clinicians.[18],[19]

CHALLENGES IN IMPLEMENTATION

Translating standardized guidelines into practice remains a formidable challenge, heavily stratified by the economic resources of the healthcare setting. Four major barriers impede effective critical value management:

Financial Constraints:

In HICs, LIS is a standard operating expense. In LMICs, purchasing a proprietary LIS equipped with a robust critical value alerting module costs between \$15,000 and \$60,000, compounded by a 15-20% annual maintenance fee.[20] International donors frequently fund capital equipment (analyzers) but routinely neglect software licenses, integration costs, and ongoing IT support.[21] Consequently, laboratories are left with isolated, offline analyzers unable to transmit urgent data.

Infrastructure Deficits:

Automated electronic alerting is inherently dependent on a stable power grid and reliable network connectivity. Unstable electricity and rolling blackouts disrupt LIS servers and Local Area Networks (LAN).[22] In Sub-Saharan Africa, the average hospital experiences power outages lasting 4-8 hours daily, and broadband speeds often remain below 5 Mbps.[23] During server downtimes, even highly automated laboratories are forced to revert to chaotic, manual paper-based backup systems, drastically increasing the risk of missed critical values.

Human Resource and Training Gaps:

There is an acute global shortage of clinical laboratory informatics specialists and biomedical engineers.[24] Furthermore, bench scientists are often not adequately trained on the medico-legal implications of CLSI GP47-A. High turnover rates in public hospitals mean that junior staff may not understand the stringent requirements for documenting read-backs or the protocol for escalating to a medical director when a ward nurse refuses to accept a result.[25]

Policy, Audit, and Compliance Issues:

A policy written on paper is useless without enforcement. Regular auditing of notification times is rare in resource-poor settings. Without continuous quality improvement (CQI) loops, staff compliance

inevitably deteriorates. TJC data highlights that over 70% of communication-related sentinel events involve a failure to either notify the provider or adequately document the notification.[4] Additionally, labs often operate in a silo, reporting the result but possessing no mechanism to verify if the clinical team actually administered the life-saving intervention (e.g., giving calcium gluconate for critical hyperkalemia).

CRITICAL VALUES IN RESOURCE-LIMITED SETTINGS: CASE STUDIES

In LMICs, high patient-to-staff ratios mean a single laboratory scientist may process upwards of 150 samples daily, leaving little time to track down physicians for critical alerts.[26] Furthermore, the proliferation of decentralized Point-of-Care Testing (POCT) devices on wards creates a blind spot; these devices rarely connect to a central database, leading to undocumented critical values.[27]

To overcome these hurdles, innovative "leapfrog" solutions are being developed. Below are two pertinent case studies illustrating successful adaptations in Africa.

Case Study 1: The Nigerian Hybrid SMS Model:

At a large tertiary teaching hospital in Lagos, Nigeria, the laboratory faced chronic delays in manual call-backs due to jammed PBX phone lines and absent ward clerks. With funding insufficient for a proprietary LIS, the informatics team developed a hybrid solution using a lightweight, locally hosted database linked to a bulk SMS API.[28] When a critical value was verified, the scientist inputted the patient ID and result into a desktop portal. The system instantly blasted an SMS to the attending physician, the on-call resident, and the ward sisters simultaneously. The SMS contained a USSD link to acknowledge receipt. This low-cost intervention reduced the median critical value notification time from 54 minutes to 14 minutes and established a time-stamped audit log, costing less than \$50 a month to maintain.

Case Study 2: AMPATH and Open-Source Automation in Kenya:

The Academic Model Providing Access to Healthcare (AMPATH) in Eldoret, Kenya, manages massive cohorts of HIV/TB patients. Managing critical values (like profound neutropenia or severe anemia) was a logistical nightmare. AMPATH successfully deployed OpenELIS (an open-source LIS) integrated seamlessly with OpenMRS (an open-source EHR).[29] Through this integration, automated flags were routed directly to clinician tablets in the wards. Because the software is open-source, the hospital avoided exorbitant licensing fees, directing funds instead toward local IT capacity building and solar-powered server backups. This

model proved that enterprise-level critical value management is achievable in Africa through open-source collaboration and donor-aligned funding.

COMPARATIVE ANALYSIS OF LIS NOTIFICATION SYSTEMS

Selecting the right system architecture is paramount. Laboratories must weigh cost, offline resilience, and integration capabilities. Table 1 outlines a comparison between proprietary and open-source Laboratory Information Systems regarding their capacity for critical value management.[20],[21],[34]

System Type/Name	Cost Model	Offline Capability	Critical Alert Mechanism	Best Fit/Setting
Epic Beaker/Cerner	High(\$100k+)	Low (Requires persistent cloud/server connection)	HER Inbox, Pager, Push Notifications, Auto-escalation	High-income, large tertiary hospitals
Sunquest LIS	Medium-High	Moderate (Local server cache)	SMS, Rule-based middleware suppression, Dashboard	HIC & well-funded private LMIC labs
Open ELIS/Bika LIS	Low (Free open-source license, IT cost only)	High (Local deployment easily supported)	Email, SMS integration via API plugins	LMIC public hospitals, resource-limited research labs
Hybrid/Custom SMS	Very Low (<\$1k)	Very High (Operates on local GSM networks)	Direct bulk SMS to basic feature phones	Rural clinics, low-tier LMIC hospitals without LAN

THE NOTIFICATION ALGORITHM (FLOWCHART)

Standardizing the workflow is critical for reducing errors. The following text-based flowchart outlines a best-practice, closed-loop algorithm for critical value

management, combining both analytical verification and clinical escalation protocols adapted from CLSI GP47-A, Joint Commission NPSG.02.03.01, and ISO 15189:2022 requirements.[9],[10],[12]

STEP 1: Identification - Analyzer flags a result

exceeding predefined critical limits.

STEP 2: Verification - Scientist verifies result integrity. Checks for pre-analytical errors (e.g., hemolysis, lipemia, clotted sample). Runs delta check against previous results.

STEP 3: Target Determination - Identify the responsible licensed caregiver (Attending physician, on-call resident, or charge nurse) via LIS or updated contact directory.

STEP 4: Notification Attempt - Attempt contact via primary method (Automated LIS Alert, SMS, or Phone Call).

Decision Point: If no acknowledgment within 15 minutes, proceed to Step 4b (Escalation to departmental head or medical director).

STEP 5: Read-Back & Documentation - Receiver verbally reads back patient ID and result. Scientist documents Time Notified, Person Notified, and Read-back confirmation in LIS/Logbook.

STEP 6: Clinical Action - Caregiver initiates life-saving clinical intervention. Quality Assurance team retrospectively audits time-to-action metrics.

STRATEGIES FOR IMPROVEMENT

To systematically improve patient safety and reporting efficiency, healthcare institutions must adopt a multi-pronged, systemic approach rather than simply blaming individuals for communication breakdowns.[30]

Multidisciplinary Governance: Form a standing critical value committee comprising laboratory directors, ICU clinicians, ward nurses, and IT staff. This committee must review and update the critical value list annually, removing tests that no longer dictate immediate life-saving action to reduce alert fatigue.[8]

Pragmatic Technology Use: Even in the absence of a multimillion-dollar LIS, laboratories can leverage low-cost, off-the-shelf tools. Using Google Sheets with conditional formatting (where cells turn red for critical limits) paired with secure messaging apps

(like corporate WhatsApp groups) can simulate LIS functionality in severely constrained environments.[31]

Mandating Closed-Loop Communication: Hospital policy must enforce the documentation of the 'Triad of Compliance': Time Notified, Person Notified, and Time of Acknowledgement. Without this triad, the loop remains dangerously open.[10]

Continuous Education and Mock Drills: Similar to code-blue drills, laboratories should conduct quarterly 'critical value drills'. Providing departments with monthly performance dashboards showing their average notification times can drive behavioral change, reportedly improving compliance by up to 35%.[32]

Targeted Infrastructure Investment: Donors and hospital management must prioritize IT infrastructure as highly as analytical equipment. Providing solar backups for LIS servers and offline-capable modules ensures that critical communications survive grid failures.[2]

FUTURE DIRECTIONS

The next decade of laboratory medicine will be defined by the convergence of predictive analytics, real-time interoperability, and mobile health.[33] We are moving from reactive notification to predictive alerting. Machine learning algorithms analyzing EHR data can predict a critical potassium drop hours before it happens based on medication administration (e.g., high-dose loop diuretics) and vital signs, prompting preemptive testing.[18]

Furthermore, the integration of laboratory data directly into mobile health (mHealth) applications will allow critical values to bypass centralized nursing stations and be pushed directly to a clinician's smartphone, complete with GPS-tracked acknowledgement and read-receipts.[34] For LMICs, the priority must be 'leapfrog' technologies - cloud-based, low-cost LIS architectures that operate on decentralized cellular networks rather than relying on unstable hospital LANs.[21] The

democratization of open-source health IT tools promises to drastically reduce the digital divide in patient safety.

CONCLUSION

Critical value reporting is a non-negotiable patient safety responsibility that links laboratory results to urgent clinical action. Although automation, middleware, and artificial intelligence can improve speed, reliability and auditability, their success depends on hospital policy, staff training and reliable infrastructure. In resource-limited settings, waiting for full automation is not realistic; practical hybrid systems - such as SMS alerts integrated with open-source LIS combined with clear governance can significantly reduce preventable harm. Ultimately, strengthening how laboratories communicate critical results is a direct investment in patient safety.

DECLARATION

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REFERENCES

1. Lundberg GD. When to panic over abnormal values. *MLO Med Lab Obs*. 1972;4(11): 19-20.
2. Howanitz PJ, Steindel SJ. Errors in laboratory medicine: critical care testing. *Clin Chim Acta*. 2005;353(1-2): 61-70.
3. Piva E, Plebani M. Interpretative commenting: a tool for improving the laboratory-clinical interface. *Clin Chem Lab Med*. 2009;30(1): 33-39.
4. The Joint Commission. Sentinel Event Data 2023. Oakbrook Terrace, IL: The Joint Commission (TJC); 2024. Available from: <https://digitalassets.jointcommission.org>. Retrieved on 15th of September, 2026.
5. Dighe AS, Jones BA, Parry G, Baron JM. Analytical performance characteristics and clinical effectiveness of critical value reporting. *Arch Pathol Lab Med*. 2011;135(6): 739-745.
6. Tate JR, Yen T, Jones GRD. Analytical performance and clinical impact of a laboratory information system critical value alert. *Clin Chem*. 2018;64(10): 1441-1448.
7. Oladipo OO, Akinyemi OO, Ogunfowora OB. Capacity building in laboratory informatics for health professionals in Nigeria. *Pan Afr Med J*. 2022;41: 112.
8. College of American Pathologists. Laboratory Accreditation Program: Chemistry and Toxicology Checklist. Northfield, IL: CAP; 2023. Available from: <https://www.scribd.com/document/743919960/Cap-Accreditation-Checklists>. Retrieved on 15th of September, 2026.
9. Clinical and Laboratory Standards Institute. Management- and significant-risk results; Approved Guideline. 1st ed. Wayne, (PA): Clinical and Laboratory Standard Institute; 2015. 100 p. (CLSI guideline GP47).
10. The Joint Commission. 2023 National Patient Safety Goals (NPSGs). Oakbrook Terrace, IL: The Joint Commission (TJC); 2023. Available from: <https://www.patientsafetysolutions.com>. Retrieved on 15th of September, 2026.
11. Jones BA, Bekeris LG, Nakhleh RE, Walsh MK, Valenstein PN. Critical value reporting in anatomic pathology: a College of American Pathologists Q-Probes study. *Arch Pathol Lab Med*. 2012;136(1):19-25.
12. International Organization for Standardization. ISO 15189:2022 Medical Laboratories - Requirements for quality and competence. Geneva; Switzerland: ISO; 2022. Available from: <https://www.iso.org>. Retrieved on 15th of September, 2026.
13. Kost GJ. Critical limits for urgent biosystem analysis. *Arch Pathol Lab Med*. 1990;114(7): 696-701.

14. Lippi G, Plebani M. The critical role of laboratory medicine during coronavirus disease 2019 pandemic and other emerging pathogens. *Diagnosis*. 2020;7(2): 63-70.
15. Wagar EA, Friedberg RC, Souers R, Stankovic AK. Assessment of clinical laboratory communication of critical values: a College of American Pathologists Q-Probes survey of 163 clinical laboratories. *Arch Pathol Lab Med*. 2007;131(12):1769-1775.
16. Genzen JR, Burnham CD, Cariappa R, Clise CE, Femia LA, Lazjak AT, et al. Effect of a critical value alert on laboratory turnaround time. *Am J Clin Pathol*. 2015;144(6): 877-882.
17. Sittig DF, Singh H. A new socio-technical model for studying health information technology in complex adaptive healthcare systems. *Qual Saf Health Care*. 2010;19(Suppl 3): i68-i74.
18. Rao JK, Weinberger M, Kroenke K. The relationship of critical value reporting to clinical outcomes. *J Gen Intern Med*. 2000;15(9):645-647.
19. Singh H, Sittig DF. Measuring and improving patient safety through health information technology: the Health IT Safety Framework. *BMJ Qual Saf*. 2016;25(4): 226-232.
20. College of American Pathologists. Laboratory information systems: 2024 survey results. Northfield, IL: CAP; 2024. Available from: <https://www.captodayonline.com>. Retrieved on 15th September, 2026.
21. Digital Square. Connecting the world for better health: funding models for digital health software. Seattle: PATH; 2023. Available from: <https://www.path.org>. Retrieved on 15th of September, 2026.
22. United Nations Industrial Development Organization. Industrial energy efficiency and power quality in Sub-Saharan Africa. Vienna: UNIDO; 2020. Available from: <https://www.unido.org>. Retrieved on 15th of September, 2026.
23. International Telecommunication Union. Measuring digital development: Facts and figures 2023. Geneva: ITU; 2023. Available from: <https://www.itu.int>. Retrieved on 15th of September, 2026.
24. National Universities Commission. Benchmark minimum academic standards for undergraduate programs in biomedical engineering. Abuja: NUC; 2019. Available from: <https://www.nuc.edu.ng>. Retrieved on 15th of September, 2026.
25. World Health Organization. Laboratory quality management system: handbook. Geneva: WHO; 2011. Available from: <https://www.iris.who.int>. Retrieved on 15th of September, 2026.
26. Petti CA, Polage CR, Quinn TC, Ronald AR, Sande MA. Laboratory medicine in Africa: A barrier to effective healthcare. *Clin Infect Dis*. 2006;42(3): 377-382.
27. Hawkins RC. Critical results reporting: is it the answer to improved patient safety? *Clin Chim Acta*. 2009;404(1):8-12.
28. Asimwe D, Bwana MB, Bangsberg DR, Ware NC, Haberer JE, Siedner MJ. Use of mobile phone SMS to improve laboratory result notification in Uganda. *Afr J Lab Med*. 2018;7(1): a672.
29. Labrique AB, Vasudevan L, Kochi E, Fabricant R, Mehl G. mHealth innovations as health system strengthening tools: 12 common applications and a visual framework. *Glob Health Sci Pract*. 2013;1(2):160-171.
30. Berwick DM. A primer on leading the improvement of systems. *BMJ*. 1996;312(7031): 619-622.
31. Garcia E, Kundu I, Fong K. The American Society for Clinical Pathology's 2019 Wage Survey of Medical Laboratories in the United States. *Am J Clin Pathol*. 2021;155(5):649-673.
32. Topol EJ. High-performance medicine: The convergence of human and artificial

- intelligence. Nat Med. 2019;25(1): 44-56.
33. Lessard L, Michalowski W, Chen Li W, Amyot D, Halwani F, Banerjee D. Predictive analytics to support real-time management in pathology facilities. AMIA Annu Symp Proc. 2017;2016: 772-778.
34. Verma N, Mamlin B, Flowers J, Acharya S, Labrique A, Cullen T. OpenMRS as a global good: Impact, opportunities, challenges, and lessons learned from fifteen years of implementation. Int J Med Inform. 2021;149: 104405.
35. Park SL, Desroches M, Sharaf RN, Melanson SE, de Baca ME, Garcia ED, et al. Comparison of open-source and commercial LIS for critical value reporting in resource-limited settings. J Pathol Inform. 2020;11: 38.