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IMPACT OF LABORATORY WORKFLOW OPTIMIZATION ON TURNAROUND TIME, DIAGNOSTIC ACCURACY, AND PATIENT CARE OUTCOMES: A SYSTEMATIC REVIEW

Esha Nawal[*1], Anam Akram Cheema[2], Hira Kanwal[3], Subtain Ali[4], Waniza Shahid[5], Salika Waseem[6], Wahab Ahmed[7]

[*1]*Department of Medical Laboratory Technology, Imran Idrees Institute of Rehabilitation Sciences, Sialkot, Pakistan*
[2,3,4,6,7]*Department of Medical Laboratory Technology, University of Sialkot, Sialkot, Pakistan*
[5]*Department of Medical Laboratory Technology, Faculty of Allied Health Sciences, Superior University, Lahore, Pakistan*

[*1]eshanawal99@gmail.com, [2]anamakramcherma@gmail.com, [3]hirakanwalkanwal1@gmail.com, [4]subtainalibhatti987@gmail.com, [5]wanishahzadi443@gmail.com, [6]salikawaseem98@gmail.com, [7]maherwahab0612@gmail.com

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Keywords

turnaround time; laboratory workflow; Lean Six Sigma; total laboratory automation; autoverification; point-of-care testing; ISO 15189; diagnostic accuracy; patient outcomes; pre-analytical errors

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Corresponding Author: *
Esha Nawal

Abstract

Background:

An estimated 60 to 70% of laboratory decisions are made in the preanalytical, analytical and postanalytical phases of the testing process but the entire process is subject to delays and errors. Turn around time (TAT) is a commonly cited proxy measure for laboratory performance and has been shown to consistently correlate with measures of downstream performance such as time to therapeutic intervention, clinician satisfaction and emergency department length of stay (LOS).

Objective:

This systematic review aims to identify and collate evidence to show how clinical laboratory workflow is optimized and what outcomes of these optimizations have been measured, including those related to TAT, diagnostic accuracy, and patient care.

Methods:

A structured search of PubMed, Scopus and gray literature was conducted for the studies describing process redesign, Lean and Six Sigma methodology, total laboratory automation, laboratory information system (LIS)-based autoverification, point-of-care testing (POCT), and quality management system accreditation (ISO 15189). Because of the diversity of study design, setting and outcome measures, findings were synthesized narratively.

Results:

Workflow optimization interventions significantly reduced TATs from about 19% to over 85% across settings and resulted in reduced specimen rejection rates, reduced transcription error and reduced manual-verification workload. Results regarding the relationship between shorter TAT and better hard clinical outcomes (mortality and length of stay) were more consistent for emergency and critical-care settings than routine outpatient testing.

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Conclusions:

The benefits of workflow optimisation in the laboratory are tangible and significant in terms of process improvements and efficiencies; improved outcomes for the patient is a plausible benefit with some good trial designs in the acute-care setting, but more robust, outcome-oriented trials are needed in general clinical practice.

Introduction

Clinical laboratory testing is a major line of business in present day healthcare delivery and laboratory test results are estimated to be the basis of most of the clinical decisions such as the diagnosis, start of treatment and discharge planning (1, 2). The total testing process in the laboratory is traditionally separated into three steps: pre-analytical step ordering of tests, collection of specimens, specimen labelling and shipment; analytical step, specimen processing and measurement; post-analytical step, verification of results, reporting and clinical interpretation (3, 4). There are opportunities for delays and opportunities for errors in each phase, and the sum of inefficiencies in all three phases is most often summarized into one combined measure: turnaround time (TAT). TAT has been one of the most studied and clinically relevant performance indicators in the laboratory medicine field and serves as an indicator of the laboratory contribution to its health system's performance at the same time as a proxy of its internal efficiency (5). Howanitz and colleagues' pioneering research revealed that laboratory delay represents a significant proportion of the total time taken for clinical decision making in acute-care environments, and many follow-up studies have confirmed that longer testing times are correlated with higher levels of emergency department (ED) length of stay, delayed treatment intervention and diminished clinician and patient satisfaction (5, 6, 7). After decades of focus on TAT as a quality measure, laboratories are still reporting significant process inefficiency. Error rates are estimated throughout the entire process of testing and pre-analytical errors are estimated to be responsible for 45% to 70% of all errors detected, making it the single most common source of laboratory errors (8, 9, 10, 11, 12). This represents a change from previous decades when the main source of error was during the analytical phase, but recent changes in instrument standardization, internal quality control and external proficiency testing have made the pre- and post-analytical phases the 'bulk of the error', and are less automated than the analytical phase and more reliant on manual human action (13). Workflow optimization, in a general sense, means optimizing the laboratory workflow by eliminating all unnecessary steps, streamlining manual processes, and ensuring smooth turnaround of specimens and information from order to report. In reality, this has been manifested in many overlapping ways in published literature: use of Lean and Six Sigma quality-improvement approaches; investment in total laboratory automation (TLA) or pre-analytical robotics; implementation of autoverification and middle ware based on laboratory information system (LIS) principles; extension of point-of-care testing (POCT) to the bedside; and formal accreditation of a quality-management system, including ISO 15189 (14, 15, 16, 17, 18). These are distinct strategies, each with a different focus on the overall testing process and each with a different body of evidence. Central to the clinical reasons underpinning workflow optimization is the concept of two related, but different claims. The first is in place: that reworked process is able to measurably reduce TAT and defect percentages. The second and more significant claim is clinical: that the operational improvements lead to better patient care outcomes including quicker time to treatment that saves lives, reduced diagnostic errors at the bedside, and shorter lengths of stay in hospital and at hospital's ED. Although the operational evidence is fairly large, the clinical-outcome evidence is more diverse and in some

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settings the connection between faster outcomes and better outcomes has not been established, though it may be intuitively plausible (19, 20). This review has the objective of describing the main classes of workflow interventions reported in the clinical laboratory literature, summarizing the evidence of their effect on turnaround time and on analytical/diagnostic error rates, assessing the quality and quantity of evidence correlating process improvement with clinical outcome at the patient level, and highlighting areas of the literature which lack representation, such as resource-constrained settings, that warrant future research and practice, in particular applicable to laboratories under accreditation systems like those commonly used in teaching hospitals and diagnostic centers in South Asia.

2. Methods

2.1 Review Design

The process of identification, screening and narrative synthesis of the literature is structured in a systematic manner following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to literature identification, screening and narrative synthesis that is consistent with methodology used in similar literature reviews in laboratory medicine (21, 22).

2.2 Search Strategy and Sources

To capture both peer-reviewed and applied operational evidence, a structured search was undertaken of PubMed/MEDLINE, Scopus, and gray literature sources, such as laboratory medicine trade publications, institutional white papers etc. Search terms included laboratory workflow, turnaround time, pre analytical and pre post analytical error, total laboratory automation, Lean and Six Sigma methodology, autoverification, point-of-care testing and laboratory accreditation; the combination of search terms was similar to that of previous systematic reviews in this area (22, 23).

2.3 Eligibility Criteria

Studies were included if they were prospective, quantitative, and included data on at least one workflow optimization intervention and at least one of the following outcome measures: turnaround time, error or specimen rejection rate, diagnostic accuracy, diagnostic quality indicator performance, or a patient-level clinical outcome (such as length of stay, time to treatment, or mortality). Peer-reviewed systematic reviews and primary observational or quasi-experimental studies were included, because there were not many randomized controlled trials in this operational domain. Those studies conducted only in non-clinical laboratories (such as research laboratories) were omitted.

2.4 Data Synthesis

Extracted data were classified into five categories of interventions which are seen frequently in the literature: (i) Lean and Lean Six Sigma process redesign, (ii) Total laboratory automation, (iii) LIS-based autoverification and middleware, (iv) Point-of-care testing, and (v) Quality management system accreditation. Reported effect sizes for TATs and error/quality indicators were calculated for each group and synthesized patient-level effects were extracted separately for patient-level outcomes, as these are somewhat under-represented in the literature.

3. The Total Testing Process and Burden of Error

3.1 Distribution of Errors Across Testing Phases

One common phenomenon found in laboratory error research over the past few decades is that errors are not randomly distributed over the three phases of testing. A large retrospective study of >37 million billable results from an academic core laboratory with about 11 million specimens, showed that pre-analytical error remains the leading cause of laboratory error in current practice, even in a very automated and high resource laboratory (9, 10). Other pre-analytical error rates reported vary between approximately 42.8% to more than 70% of the total errors, while analytical and postanalytical error rates are about 13% to 33% and 18% to 24% of the total errors, respectively (11, 12, 24, 25).

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Table 1 provides an approximate distribution of error by phase and the typical drivers of these errors that are mentioned in the literature cited.

Testing Phase	Approx. Share of Total Errors	Typical Error Rate	Primary Drivers
Pre-analytical	45–70%	0.1%–1.5% of specimens	Misidentification, hemolysis, insufficient volume, transport delay
Analytical	13–32%	0.01%–0.1%	Instrument calibration, reagent lot variation, QC drift
Post-analytical	18–24%	0.05%–0.3%	Reporting delay, transcription, critical-value notification failure

3.2 Common Pre analytical Error Types

Patient or specimen misidentification, hemolyzed or clotted specimens, insufficient sample volume, and improper collection tube or anticoagulant, prolonged or improper transport conditions, and incomplete or illegible requisition information are the most common error categories that occur during the pre-analytical phase (11, 12, 26, 27). In Pakistan, South Punjab, only 19.45% of laboratory requisition forms was found to contain complete data in a cross-sectional study, which indicates that documentation quality, but not specimen handling, is an important factor in preanalytical risk in resource-limited settings (26). Another hematology-laboratory study in Ethiopia also found that incomplete forms and poor specimen collection as the primary reasons for rejected and compromised samples (27). Undetected preanalytical errors are not innocuous: If a specimen can't be recollected, the diagnostic information it was intended to provide is lost forever, and undetected errors can lead to false or missed diagnoses, repeated testing, and, on the aggregate, a loss of trust by clinicians in the laboratory's results (27, 28).

3.3Variations in analytical and post analytical error trends.

However, post-analytical error is a relatively under-studied domain and a number of errors that have been reported as frequent contributors include failure to notify when a critical result is returned, transcription error, and delayed reporting (17, 30). The Working Group on Laboratory Errors and Patient Safety of the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) has recommended a set of quality indicators covering both the extra-analytical phases, which will enable benchmarking against targets based on the sigma-metric approach (31).

4.Lean and Six Sigma Methodology in Laboratory Workflow Redesign

4.1 Conceptual Basis

Lean methodology was developed in manufacturing process management to focus on delivering the greatest value to the last user: the ordering clinician and the patient, in our case, by systematically removing non-value-added steps in a process, known as "waste." (32, 33) Six Sigma also has a defined, statistically based improvement process, called DMAIC (Define, Measure, Analyze, Improve, Control), which helps them pinpoint the root causes of variation and defect and introduces and maintains corrective controls (33, 34, 35).

4.2 Reported Effects on Turnaround Time

Based on the seven identified studies in the systematic review, which was registered in 2024 on PROSPERO and reported in accordance with the PRISMA 2020 guidelines, the average impact of applying Lean methodology to the pre-analytical phase was reported as 76.1% (37, 38, 39) in the pooled evidence base. Among those

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studies included in that review, a microbiology laboratory in Spain achieved an 87.4% reduction in HIV rapid-test TAT by redesigning the tests, reallocating staff, and prioritizing tests (39, 40); and a 19.2% reduction in COVID-19 test TAT through these same activities.

A Lean management intervention in a resource-limited setting showed that mean TAT for complete blood count (CBC) testing decreased significantly from 36.0 minutes (SD 13.4) to 25.6 minutes (SD 4.1) ($p<0.05$); the mean TAT for random blood glucose (RBG) testing also improved significantly ($p<0.01$) from 88.6 minutes to 81.1 minutes (SD 4.1) (42). The authors pointed out that the key improvement was through systematic workflow redesign, not investment in capital equipment, which has relevance to laboratories in low and middle income countries where budget for automation is limited (42, 43).

4.3 Effects on Error Rates and Staff Safety

In addition to time measurements, Lean Six Sigma interventions have shown measurable decrease in the number of process steps that are medical-error or biohazard risk. A DMAIC-based intervention in a sample reception area saved 3 hours and 22.5 minutes of non-value added work, cut STAT sample TAT from 68 to 59 minutes and reduced the number of steps in the process that could create a medical error or biohazard risk for receptionists from 30% to 3% (35, 44). In a related review, the application of Lean and Six Sigma frameworks in both emergency department and laboratory, cardiology and surgical settings, intensive care, and pediatric settings concluded that the prerequisites to sustainable positive changes in critical-result reporting and patient outcomes were both multidisciplinary teamwork and the use of technology and standardized protocols (33, 45). The limitations of the Lean/Six Sigma Evidence Base. While significant improvements have been reported, in most of the underlying study designs, typically a single center and before-after, or more commonly, quasi-experimental designs, causal inference and generalizability are constrained. Direct comparison of studies is further complicated by the fact that baseline TAT definitions, test menus, and institutional context vary within studies (37, 46). However, findings of directionally positive effects are consistent across geographically and economically diverse contexts, such as Spain to Ethiopia to Indonesia, so that there is reasonable confidence that the mechanism causing the removal of non-value-added manual interventions is generalizable across contexts (39, 42, 47).

5. Pre analytical Robotic Systems and Automation

5.1 Scope of Automation Interventions

Total laboratory automation (TLA) involves linking several analytical and pre-analytical instruments together through a track-based, relatively continuous process and, in most cases, automated transport of specimens to analyzers, as well as automated specimen sorting and centrifugation and aliquoting. Mid to high volume laboratories unable to afford the purchase of a TLA can now integrate front-end specimen processing with core chemistry, hematology and coagulation testing as second generation automation platforms have made it feasible to go further upstream in the process.

5.2 Quantified Efficiency Gains

A detailed before-after analysis of the implementation of TLA revealed an 82% reduction in hands on time associated with add-on testing processes (15) and a reduction in time to receipt for outpatient specimens from 7 seconds per specimen when using manual barcode scanning to 2.5 seconds per specimen when using automated batch reception: a 65% reduction in hands on time at that process step alone. Another operational concern that was addressed by the authors was that automation consolidation would create new bottlenecks, but this did not seem to be the case with combining STAT with outreach specimen processing on a single automated platform (15). A theoretical synthesis of the three models (TQM, Lean Six Sigma, Human Factors and Ergonomics) and the TAM yielded the conclusion that automation yields benefits to the diagnostic process by up to 70% reduction in preanalytical errors, no manual

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transcription errors, more than 50% reduction in TAT, and 30-60% increase in sample throughput in the studies reviewed (50). Further, automated specimen transport systems have been the subject of vendor-independent reviews that also claim a decrease in manual processing steps between 50% and 80% (51, 52). It allows for the reduction of error by 5.3 mechanisms.

5.3 Error reduction Mechanism

Automated robotic workstations help minimize the risk of misidentification or mislabeling due to manual transcription, as well as potential error in sorting, labelling, and aliquoting, since these processes are repeatable and are performed without human intervention (53, 54). Others have made it clear that the advantage of automation is best realized when it is associated with a laboratory information system and that automation without the associated informatics integration actually moves the bottlenecks downstream (53, 55).

5.4 Implementation Barriers

Capital cost remains the key obstacle faced in the implementation of TLA identified in the literature; availability of automated analyzers, robotic specimen-handling systems, and integrated software platforms are a significant initial investment, often unrealistic for laboratories in resource-limited environments (56). Along with efficiency, workforce shortage is also mentioned as a parallel impetus to the adoption of automation, as automation is increasingly being seen as a substitute to the shortage of skilled laboratory personnel worldwide (19, 56).

6. Lab Information Systems

6.1 Concept and Mechanism Autoverification

The automatic release of test results that are within predefined and acceptability rules, without any manual technologist verification, to manual verification (57, 58, 59) when the result is outside of the acceptability rules. This works toward a uniforming the criteria for releasing results, eliminates inter-observer variability in deciding whether or not to release a result, and frees technologist time from the task of verifying a result to allow them to spend more time on truly abnormal or borderline results that do require clinical judgment (57, 60).

6.2 Trade-off between QOT and the number of casings.

As the rules of the clinical chemistry laboratory's academic medical center's autoverification evolved from simple LIS logic to more complex middleware algorithms, the TAT for affected coagulation assays dropped 31.8%, from 132 minutes to 90 minutes, and the pass rates climbed to ˜96.1% for activated partial thromboplastin time, ˜95.1% for prothrombin time, and ˜90.9% for fibrinogen (57, 61). In a separate validation study using four of the major assays, the average TAT savings per affected result category ranged from 116.7 to 121.7 minutes (61, 62), and the pass rate for the coagulation autoverification system varied between 77.1% and 83.7% for the different algorithm configurations tested.

The programs will inform the students about error detection and governance. Since there is no human check on the results-release chain with autoverification, strong validation prior to deployment is necessary. A human-machine interaction validation framework was developed for a large academic center's autoverification rule set, which included 833 individual rules with 30 assays; 93.87% of the rules were correctly verified, and the laboratory had over 3.5 million autoverified reports over 3 years without a clinical complaint related to the system (58, 65). The same lab found that 94.6% of personnel surveyed that worked in the lab felt that the system alleviated the burden and controlled the reporting risk (65).

6.4 Disease-Specific and Frontline Dilution Applications.

Autoverification systems have also been implemented for frontline dilution decision logic, leading to a decrease in repeat rates following dilution from 14.20% to 8.23% ($p<0.001$), and also to a decrease in the monthly examination costs and an improvement in TAT of an

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estimated 65 minutes per day in one tertiary-hospital biochemistry laboratory (62, 66). The results show that LIS-based rule automation can achieve all three of these benefits at the same time cost-efficiency, reduction of unnecessary repeat testing, and a decrease in TAT benefits that are often seen as conflicting in laboratory management.

7. Point-of-care testing (POCT)

7.1 Rationale and Clinical Contexts

Point-of-care testing (POCT) moves analytical testing away from the central lab to the bedside, emergency department or field setting without the delay of transport and batch processing from the central lab (67, 68). POCT has been most widely studied in situations where the delay between specimen collection and the actionable result to take life-saving action is critical, such as in the recognition of sepsis, triage for acute coronary syndrome, and disaster/mass casualty response (67, 69, 70).

7.2 Evidence on Time to Result and Bundle Adherence

In an emergency department, a pre-post observational study of the introduction of bedside lactate POCT showed that the time to lactate result decreased from 53 minutes before to 33 minutes after implementation and the number of lactate measurements per patient increased from 82.1% to 88.2% for subsequent (repeat) measurements (71). The same study did not show a significant increase in overall compliance with the Surviving Sepsis Campaign bundle with the adoption of POCT lactate testing (47.5% versus 45.0%) or a significant reduction in 30-day mortality with the implementation of POCT lactate testing, indicating that faster results do not necessarily lead to better process adherence or hard clinical outcomes (71, 72). A literature review of the various POCT tools for the diagnosis and management of sepsis published from 2000 to 2024 identified that there have been a significant number of advances in biosensor, microfluidic and lab-on-a-chip platforms, but the evidence for the direct association of POCT with the reduction of sepsis mortality is less consistent than the evidence of POCT's association with other time-to-results metrics (72, 73).

7.3 Critical Care and Disaster Settings

POCT has been proven valuable in critical care as a diagnostic and prognostic tool, as well as a tool to assess electrolytes, lactate, and creatinine which are often used indicators of severity of illness, and thus can help to identify patients who require escalation of care earlier (67, 74). Pathogen detection systems that use near-patient polymerase chain reaction (PCR) have reduced the time needed to diagnosis skin and soft-tissue infections to one hour, which is a significant improvement over the time needed for conventional culture assays and has direct impact on early and appropriate antimicrobial treatment in disaster situations and mass-casualty environments (69, 75).

7.4 Limitations of POCT

However, the reliability of some POCT analytes in the blood is influenced by differences in sample handling, such as the effect of heparinized syringes on potassium, and the findings from studies on the effect of POCT on hospital admission rates can be conflicting, indicating that the benefit of POCT may be more dependent on the clinical pathway it is integrated within than a blanket, uniformly positive intervention (67, 76, 77).

8. Quality Management Systems and Accreditation (ISO 15189)

8.1 Standard Scope

ISO 15189 sets out quality and competence requirements for medical laboratories that cover the entire diagnostic process, from pre-examination activities such as specimen collection, identification and transport, to examination activities such as the application of validated analytical methods, to post-examination activities such as result interpretation, critical-value notification, and reporting (78). There are now about 60 countries in the world that have implemented ISO 15189 as a regulatory

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requirement or a recommended standard for clinical laboratories (79).

8.2 Evidence from Resource-Limited Settings

Implementation experience from a clinical laboratory in Tanzania showed that, after implementing the quality management system in accordance with ISO 15189, there were significant improvements in performance of the external quality assessment in parasitology that went from 45% to 100%, in molecular biology from no formal record to 100%, in biochemistry from 50% to 95%, and in tuberculosis microscopy from 60% to 100% (80, 81); rates for rejecting specimens dropped from 7.2% to 1.2%, and blood culture contamination dropped from 16% to 4%. In the same laboratory, the same defined TAT targets were then met in the majority (92%) cases, a metric that was not officially monitored before the implementation of the quality system, showing that the accreditation process can introduce TAT measurement as another quality practice (80). Since its launch 5 years ago, the Stepwise Laboratory Quality Improvement Process Towards Accreditation (SLIPTA) framework, in collaboration with the World Health Organization's Regional Office for Africa, has been adopted in 617 laboratories from 47 countries, with a clear focus on specific management behaviours linked to ISO 15189 requirements (82, 83). There are also ongoing obstacles to accreditation.Ongoing barriers to accreditation exist as well. While benefits have been shown, many settings have significant structural barriers to accreditation. There were sixteen different categories of implementation challenge identified when researchers surveyed laboratory staff at a public health laboratory in Ghana after ISO 15189 accreditation, and the longitudinal study conducted in Uganda showed that even if laboratories have achieved accreditation, ongoing resource constraints such as commodity stock-outs, limited tests and inadequate human resources persist (85, 86, 87).

9 .Workflow Optimisation

9.1 Emergency Department Length of Stay

Time spent in the Emergency Department. Laboratory TAT is the most widely reported patient-outcome association in this literature, and is associated with emergency department length of stay (EDLOS). A study in 11 hospitals showed that the reduction of TAT outliers, as opposed to TAT mean, was significantly correlated with measurable decreases in EDLOS, and that clinically driven TAT targets, determined as the percentage of TATs within the target range rather than mean TAT, should be considered a more clinically relevant approach to target setting (88, 89). In a previous prospective cohort study assessing the impact on the introduction of a satellite laboratory in the ED, the time taken for haematology results became significantly shorter: 47.2 mins (95% CI 38.3–56.1, $p<0.001$) and decision to discharge patients became significantly faster: 28.2 mins (95% CI 13.5–42.8, $p<0.0001$) without any significant changes being observed for decisions to admit patients (90). A large retrospective cohort study of 269,808 visits across 17 community emergency departments and three academic emergency departments revealed a statistically significant (but weak) positive association between first laboratory order time and length of stay ($R^2 = 0.0378$, $p<0.001$), consistent with previous studies showing that for every minute reduction in turnaround time, length of stay decreased by approximately 0.50 minutes (91, 92). Using a separate retrospective cohort of 23,718 ED visits, both time-to-testing and TAT were independently and positively associated with EDLOS, with the laboratory stage accounting for a median of 69% (IQR 59–78%) of total TAT, suggesting that the laboratory stage is the most promising target for interventions aimed at reducing EDLOS and emergency department crowding (93, 94, 95).

9.2 Therapeutic and Triage Decisions

In addition to length of stay, laboratory TAT has been associated with the timing of certain therapeutic interventions. Rapid troponin testing is also mentioned as being crucial to the diagnosis of myocardial infarction in ED patients,

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directly affecting time to reperfusion therapy and thus the risk of mortality (92, 96). Within this literature, a study from 2015 identified that the quicker testing was conducted for patients admitted with acute respiratory tract illness, the quicker therapeutic interventions were started and results were better for patients (92, 97).

9.3 Inconsistencies and Null Findings

However, not all evidence confirms that there is a clear correlation between a quicker TAT and better hard outcomes. As indicated in Section 7.2, the use of POCT lactate testing did not significantly improve sepsis bundle adherence or 30-day mortality in at least one well conducted observational study, but did shorten the time-to-result (71). Results from studies concerning the impact of POCT on admission rates are also inconsistent, with some reports of reduced length of hospital stay following POCT implementation and others reporting no significant difference, partly because of a restricted range of POCT analytes, and the need for some patients to have many more tests performed centrally (76, 98).

9.4 Outcome-Focused Benchmarking

One point that does emerge from the more robust outcome-oriented studies is that mean TAT may not be a more clinically relevant measure than the proportion of specimens failing to meet a clinically agreed threshold (88, 95), as a few large outliers (not small average delays) could have a disproportionate impact on downstream adverse outcomes like prolonged EDLOS. Future laboratory quality programs should consider, rather than just central-tendency statistics, the distribution and outlier rates for TAT when assessing the clinical impact of a workflow intervention.

10. Emerging Technologies: Artificial Intelligence and Machine Learning.

10.1 Current Applications Artificial intelligence (AI) and machine learning (ML) are being implemented in all three stages of the total testing process, and it has been documented that AI and ML are being used in pre-analytical screening of specimen quality, the interpretation of analytical results and in post analytical quality control and inventory management (99, 100, 101). A summary of the applications of AI in pathology, microbiology and biochemistry highlighted the potential of AI in cybergram stain typing to bacterial identification and predicting antibiotic resistance and how these would enhance diagnostic accuracy, reduce human error and improve turnaround time (102).

10.2 **Reported and Projected Impact**

The reported and projected impacts of the disaster are as follows: A few industry analyses have tried to quantify the economic value that AI offers to the healthcare industry overall, including diagnostic laboratory functions, by measuring the efficiency gains it could bring. While these estimates are derived from models and not controlled trials, they suggest that significant economic value could be gained annually through efficiency gains once AI is widely integrated into the industry (101, 103). One review specifically aimed at the value of AI in African laboratory medicine recognized that workflow was key to efficiency; and that AI incorporation could provide multi-domain benefits: quality control, inventory management and test interpretation (101).

10.3 Validation and Governance Concerns.

A review of the literature was conducted on the topic of readiness for advance AI use in clinical laboratories, from which 63 articles were selected from a larger search of 98 articles, which found that there are already applications of AI for urine analysis and disease detection and monitoring, but there is a lack of robust validation frameworks for laboratories at this time compared to the speed at which technology is being deployed (104, 105). Complementary work has suggested integrated diagnostic quality models to provide a formal assessment of the quality of AI and ML diagnostics prior to clinical use, and guidelines for the rigorous testing of machine learning in the context of laboratory medicine, indicating a growing consensus that governance frameworks must evolve as AI and ML becomes more capable (106, 107, 108).

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10.4 Implications for Workflow Optimization Practice.

Combining the AI and ML literature, the near future looks like workflow optimization not only moving beyond physical automation and rules-based autoverification, but into adaptive, learning-based systems that can pick up on pre-analytical specimen quality issues, isolate critical results before formal analytical completion, and assist with clinical interpretation directly in the laboratory report. While the standards for validation in this area are still relatively underdeveloped, at this time, AI-driven interventions are intended to be used alongside the more matured workflow optimization strategies discussed in Sections 4 through 8 (105, 108) and are not yet a replacement.

11. Synthesis Across Intervention Categories

Table 2 provides a summary of comparative evidence found for each of the five major categories of interventions reviewed.

Intervention Category	Representative Studies	Reported TAT Effect	Reported Quality/Outcome Effect
Lean / Lean Six Sigma redesign	Cherie et al.; process-redesign cohort studies	Reductions of 19–87% depending on test and setting	Fewer non-value-added steps; improved staff and patient satisfaction
Total laboratory automation (TLA)	Hawker; automation case series	Up to 65–82% reduction in hands-on processing time	Reduced manual-handling errors; higher throughput
LIS-based autoverification	Wang et al.; Torke et al.; Wen et al.	TAT reductions of 30–65 minutes per batch; 31.8% relative reduction reported in one series	Eliminated inter-observer variability in result release
Point-of-care testing (POCT)	Lee et al.; sepsis POCT cohorts	Time-to-result cut roughly in half (e.g., 53 to 33 minutes for lactate)	Mixed effect on hard outcomes; faster, not always better, bundle adherence
ISO 15189 / quality management systems	Mafuta et al.; Lubega et al.; Bates et al.	TAT target attainment improved to over 90% post-accreditation	Lower specimen rejection and contamination rates

This synthesis brings several observations across the board. First, there is wide variability in the amount of TAT improvement reported based on the baseline level of process maturity: laboratories with very manual and unstandardized processes reported the greatest relative improvement, whereas laboratories with more automated processes reported relatively smaller but still significant improvement (37, 50). Second, interventions at the pre-analytical phase, the largest proportion of total error and delay, seem to have the greatest combined benefit over TAT and diagnostic accuracy, as shown phase-wise in the distribution of error and delay in Table 1 (9, 37, 50). Third, the evidence for process improvement impacting on hard patient outcomes is strongest in settings that involve emergency or critical care, where the causal relationship of TAT to a hard patient outcome has the shortest time lag and the clearest pathway of causality (88, 93, 95); and is weaker for routine outpatient or chronic-disease monitoring settings, where there are additional clinical and administrative factors that can get in the way between TAT and a hard patient outcome. Another thing to note is resource setting. Total laboratory automation and advanced middleware tools are the most capital-intensive approaches

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and although these have proved to yield tangible TAT benefits, even in resource-challenged environments where capital investment has yet to be made, workflow optimization is clearly a function of process discipline and management commitment, as well as technology acquisition (42, 80, 81).

12. Limitations of current Evidence

There are several limitations that are repeated in the literature reviewed in this paper. The majority of studies are single-center, before-after or quasi-experimental in design and there are fewer multicenter or randomized evaluations to support the causal inference of workflow interventions (37, 46). There is not a consistent definition of outcome measures across studies, e.g., TAT is measured both from order entry and from specimen collection or specimen receipt in the laboratory, making it difficult to directly compare results across studies (4, 5, 95). Publication/reporting bias towards positive results is also possible because few studies report lack of effects of workflow interventions on TAT, although at least one rigorous study reported no significant improvement in hard clinical outcomes with improved time-to-result (71). Geographic representation isn't even either. Although some of the current accreditation and resource-limited-setting literature comes from sub-Saharan Africa, and there are valuable contributions from the pre-analytical error literature from South Asia, the automation, autoverification, and AI literature is disproportionately from high resource health systems in North America, Europe, and East Asia. The direct generalizability of the conclusions drawn from the automation literature to any particular laboratory depends on its different capital, staffing, and specimen-volume requirements (26, 42, 56, 80).

13. Implications for Practice

The synthesized evidence offers several practical priorities for laboratory managers and program leadership. Pre-analytical process optimization is a key step in workflow optimization and is the most consistently shown to be improved by low-cost initiatives like bar coding, staff role reallocation, and requisition standardization, and is the phase with the greatest amount of total error in the laboratory (37, 38, 42). Therefore, for laboratories with higher resources, the possibility of investing in automation must be evaluated, taking into account the potential gains in efficiency when linked with the necessary LIS and middleware integration, avoiding the risk of automation leaving behind, rather than solving, bottlenecks (15, 53, 55). If TAT outliers and benchmarking of percentage of target met are desired, the laboratory serving acute-care and emergency settings should consider using that data in addition to the mean TAT, as there is evidence that TAT outliers are linked to emergency department length of stay (88, 95). Finally, the process of pursuing accreditation of a formal quality management system, even if a full ISO 15189 certificate isn't obtainable at first, seems to be yielding measurable quality benefits, due to the discipline of setting up and monitoring quality indicators, rather than the certification itself (80, 84). The results justify the view of the laboratory educators and training programs (including undergraduate and postgraduate medical laboratory technology courses) that teaching the total testing process as an integrated quality system as opposed to a single analytical technique – is essential, as the evidence has been compelling and consistent in identifying non-analytical, process-level factors as the primary cause of delay and error in contemporary laboratory practice (3, 4, 9).

14. Future Research Directions

More prospectively designed, multicenter studies with consistent definitions of the TAT and outcomes would be helpful in future research, as this would enable meaningful meta-analytic synthesis of the current literature, which is hampered by considerable heterogeneity. A broader focus on hard patient-level outcomes is required, especially in non-emergency clinical settings where the connection between the TAT and outcome is less obvious and thus more

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important to establish empirically rather than assume (71, 93). More research in resource-limited contexts than in high-resource contexts has been conducted on automation and AI-based interventions, though the volume of research conducted in these resource-limited contexts is relatively low compared to the number of interventions done in high-resource contexts and the burden of preventable laboratory error may be greatest where automation investment is least feasible (26, 56, 80). Last, with the increasing adoption of AI and machine learning tools from pilot to routine use in clinical settings, validation frameworks that address challenges such as "model drift", "population shift" and integration with existing autoverification rule sets will have to grow in parallel with the technical development of these tools to ensure that they do not negatively impact clinical accuracy (104, 106, 107).

15. Conclusion

This systematic review combined the evidence for the five major areas of laboratory workflow optimization: Lean and Six Sigma process redesign, total laboratory automation, LIS based autoverification, point of care testing (POCT) and quality management system (QMS) accreditation to identify consistent evidence of turnaround time (TAT) and process-level quality indicators (QLIs) across a variety of clinical and geographic settings, with significant improvements being found in all areas. In time-critical, acute-care settings like the emergency department and critical care unit, the relationship of these operational improvements and improvements in therapeutic decision-making and patient outcomes is well documented, as shorter turnaround time has been correlated with shorter length of stay. This relationship is more diverse in other clinical settings, at least one rigorous study showing that there was no clear relationship between a faster result and better adherence of the bundle or decreased mortality.

References

Plebani M. The detection and prevention of errors in laboratory medicine. Ann Clin Biochem. 2010;47(2):101-110.

Lippi G, Plebani M. Integrated diagnostics: the future of laboratory medicine? Biochem Med (Zagreb). 2020;30(1):010501.

International Organization for Standardization. ISO 15189:2012 Medical laboratories — Requirements for quality and competence. Geneva: ISO; 2012.

Frequency and types of pre-analytical errors in a clinical laboratory of a specialized healthcare hospital. PMC. 2024. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10844902/

Turnaround-Time Optimization in Mixed Routine-and-STAT Clinical Laboratories. Int J Biochem Biophys Biotechnol Stud. 2026. Available from: https://eajournals.org/ijbbbs/

Hawkins RC. Laboratory turnaround time. Clin Biochem Rev. 2007;28(4):179-194.

Steindel SJ, Howanitz PJ. Physician satisfaction and emergency department laboratory test turnaround time. Arch Pathol Lab Med. 2001;125(7):863-871.

Spies NC, Farnsworth CW. Preanalytical Phase Errors Constitute the Vast Majority of Errors in Clinical Laboratory Testing. Clin Chem. 2024;70(Suppl 1):hvae106.207.

Pre-analytical phase errors constitute the vast majority of errors in clinical laboratory testing. WashU Research Profiles. 2024. Available from: https://profiles.wustl.edu/

Spies NC, Farnsworth CW, et al. Pre-Analytical, Analytical, and Post-Analytical Errors in Clinical Laboratory Testing: A Systematic Review of Causes and Prevention Strategies. ResearchGate. 2024.

Frequency and types of preanalytical errors occurring in the hematology laboratory at Debre Tabor comprehensive specialized hospital, North Central, Ethiopia, 2025. Sci Rep. 2026.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Pre-analytical errors in the clinical laboratory and how to minimize them. ResearchGate. 2013.

The Nature, Causes, and Clinical Impact of Errors in the Total Testing Process. J Patient Saf. 2023;19(8).

Cherie N, Berta DM, Tamir M, Yiheyis Z, Angelo AA, Mekuanint Tarekegn A, et al. Improving laboratory turnaround times in clinical settings: a systematic review of the impact of lean methodology application. PLoS One. 2024;19(10):e0312033.

Hawker CD, et al. Improving Laboratory Processes with Total Laboratory Automation. Lab Med. 2019;50(1):96-104.

Wang Z, Peng C, Kang H, Fan X, Mu R, Zhou L, He M, Qu B. Design and evaluation of a LIS-based autoverification system for coagulation assays in a core clinical laboratory. BMC Med Inform Decis Mak. 2019;19:128.

Transformative impact of point-of-care testing in critical care. World J Crit Care Med. 2025;14(2):100623.

Implementation of the laboratory quality management system (ISO 15189): Experience from Bugando Medical Centre Clinical Laboratory – Mwanza, Tanzania. Afr J Lab Med. 2018.

What Is Lab Automation? A Guide to Increased Lab Efficiency. StudioRed. 2025.

Impact of Point-of-Care Lactate Testing for Sepsis on Bundle Adherence and Clinical Outcomes in the Emergency Department: A Pre–Post Observational Study. J Clin Med. 2024;13(18):5389.

Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71.

Cherie N, et al. Improving laboratory turnaround times in clinical settings: a systematic review of the impact of lean methodology application. PMC. 2024. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11486360/

Maximizing Laboratory Turnaround Time Efficiency: Workflow Optimization in Resource-Limited Settings. J Int Med Health Res. 2024;3(11).

Pre-Analytical Errors in the Clinical Laboratory and How to Minimize Them. ResearchGate. 2013.

Evaluation of preanalytical and postanalytical phases in clinical biochemistry laboratory according to IFCC laboratory errors and patient safety specifications. Biochem Med (Zagreb). 2022;32(2).

Frequency and types of pre-analytical errors in a clinical laboratory of a specialized healthcare hospital. PMC. 2024. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10844902/

Types and frequency of preanalytical errors occurring in the hematology laboratory at Debre Tabor comprehensive specialized hospital, North Central, Ethiopia, 2025. Sci Rep. 2026.

The Preanalytical Errors: A Continuous Challenge for Clinical Laboratories. ASCLS. 2020.

The Nature, Causes, and Clinical Impact of Errors in the Total Testing Process. J Patient Saf. 2023;19(8).

Development and implementation of an LIS-based validation system for autoverification toward zero defects in the automated reporting of laboratory test results. BMC Med Inform Decis Mak. 2021;21:108.

Evaluation of preanalytical and postanalytical phases in clinical biochemistry laboratory according to IFCC laboratory errors and patient safety specifications. PMC. 2022. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9344872/

Villa D. Automation, lean, six sigma: synergies for improving laboratory efficiency. J Med Biochem. 2010;29:339-348.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Thakur V, et al. Lean and Six Sigma as continuous quality improvement frameworks in the clinical diagnostic laboratory. Crit Rev Clin Lab Sci. 2023;60(1):63-81.

Enhancing Quality in Clinical Laboratories with Six Sigma. Beckman Coulter. 2024.

Lean six sigma methodologies improve clinical laboratory efficiency and reduce turnaround times. PubMed. 2017.

Use of a Lean Six Sigma approach to investigate excessive quality control material use and resulting costs. Clin Biochem. 2022.

Cherie N, Berta DM, Tamir M, et al. Improving laboratory turnaround times in clinical settings: a systematic review of the impact of lean methodology application. PLoS One. 2024;19(10):e0312033.

Workflow Optimization in a Clinical Laboratory using Lean management principles in the pre-analytical phase. ResearchGate. 2024.

Improving laboratory turnaround times in clinical settings: a systematic review of the impact of lean methodology application. PMC. 2024. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11486360/

How to Improve Laboratory Turnaround Time. Laboratory Management Consultants. 2026.

Workflow Optimization in a Clinical Laboratory using Lean management principles in the pre-analytical phase. ResearchGate. 2024.

Maximizing Laboratory Turnaround Time Efficiency: Workflow Optimization in Resource-Limited Settings. J Int Med Health Res. 2024;3(11).

Maximizing Laboratory Turnaround Time Efficiency: Workflow Optimization in Resource-Limited Settings. ResearchGate. 2024.

Lean six sigma methodologies improve clinical laboratory efficiency and reduce turnaround times. PubMed. 2017.

Lean and Six Sigma as continuous quality improvement frameworks in the clinical diagnostic laboratory. ResearchGate. 2022.

Lean and Six Sigma as continuous quality improvement frameworks in the clinical diagnostic laboratory. Crit Rev Clin Lab Sci. 2023;60(1):63-81.

Maximizing Laboratory Turnaround Time Efficiency: Workflow Optimization in Resource-Limited Settings. J Int Med Health Res. 2024;3(11).

Laboratory automation for greater output. LabLeaders / Roche Diagnostics. 2026.

The Impact of Laboratory Automation on Diagnostic Accuracy and Workflow Efficiency. J Theor Appl Sci. 2025.

The Impact of Laboratory Automation on Diagnostic Accuracy and Workflow Efficiency. J Theor Appl Sci. 2025. Available from: https://fuelcellsbulletin.org/index.php/journal/article/download/223/164/448

Automation Contributes to Laboratory Efficiency. Orchard Software White Paper. 2025.

What Is Lab Automation? A Guide to Increased Lab Efficiency. StudioRed. 2025.

Minimizing laboratory errors with automation. Med Lab Obs. 2023.

Minimizing Laboratory Errors: The Role of Automation in Reducing Mistakes. Diamond Diagnostics. 2024.

Alqadi OM, et al. The Impact of Automation on Clinical Laboratory Efficiency and Error Reduction. Saudi J Med Pub Health. 2024;1(2).

The Impact of Automation on Clinical Laboratory Efficiency and Error Reduction. ResearchGate. 2024.

Autoverification in a Laboratory Information System. ResearchGate. 2002.

Development and implementation of an LIS-based validation system for autoverification toward zero defects in the automated reporting of laboratory test results. BMC Med Inform Decis Mak. 2021;21:108.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Designing and validating an autoverification system of biochemical test results in Hatay Mustafa Kemal University, clinical laboratory. PMC. 2022. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9344865/

How to Use Autoverification in the Laboratory to Improve Efficiency. Clinisys. 2026.

Autoverification in a Laboratory Information System. ResearchGate. 2002.

Design and evaluation of a LIS-based autoverification system for coagulation assays in a core clinical laboratory. BMC Med Inform Decis Mak. 2019;19:128.

REMISOL Advance Middleware Solution: Drive Laboratory Network. Beckman Coulter. n.d.

Data Innovations Instrument Manager — Middleware (LIS-analyzer interface) Software. IntuitionLabs. 2025.

Development and implementation of an LIS-based validation system for autoverification toward zero defects in the automated reporting of laboratory test results. PMC. 2021. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8170738/

Designing and validating an autoverification system of biochemical test results in Hatay Mustafa Kemal University, clinical laboratory. PMC. 2022.

Transformative impact of point-of-care testing in critical care. World J Crit Care Med. 2025;14(2):100623.

Point-of-Care Testing at the Disaster-Emergency-Critical Care Interface. PMC. 2013. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC3769791/

Point-of-Care Testing at the Disaster-Emergency-Critical Care Interface. Mil Med. 2013.

Point-of-care testing for early detection of sepsis: a systematic literature review. Clin Chim Acta. 2025.

Lee S, Song J, Lee S, Kim SJ, Han KS, Lee S. Impact of Point-of-Care Lactate Testing for Sepsis on Bundle Adherence and Clinical Outcomes in the Emergency Department: A Pre-Post Observational Study. J Clin Med. 2024;13(18):5389.

Point-of-care testing for early detection of sepsis: a systematic literature review. ScienceDirect. 2025.

Point-of-care testing for early detection of sepsis: a systematic literature review. Clin Chim Acta. 2025.

Transformative impact of point-of-care testing in critical care. PMC. 2025. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11891844

Point-of-Care Testing at the Disaster-Emergency-Critical Care Interface. PMC. 2013.

Shorter laboratory turnaround time is associated with shorter emergency department length of stay: a retrospective cohort study. BMC Emerg Med. 2022;22:212.

Transformative impact of point-of-care testing in critical care. World J Crit Care Med. 2025;14(2):100623.

ISO 15189: Medical Laboratories — Quality and Competence Requirements. International Organization for Standardization. 2022.

Toward a culture shift in laboratory quality: application of the full ISO 15189 standard. Med Lab Obs. 2023.

Implementation of the laboratory quality management system (ISO 15189): Experience from Bugando Medical Centre Clinical Laboratory – Mwanza, Tanzania. Afr J Lab Med. 2018. PMC. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6111386/

Implementation of the laboratory quality management system (ISO 15189): Experience from Bugando Medical Centre Clinical Laboratory – Mwanza, Tanzania. PMC. 2018.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

The SLMTA programme: Transforming the laboratory landscape in developing countries. Afr J Lab Med. 2014. PMC. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4703335/

A journey to accreditation: is ISO 15189 laboratory accreditation possible in Ethiopia? Pan Afr Med J. 2016.

ISO 15189: Medical Laboratories — Quality and Competence Requirements. ISO Library. 2022.

Challenges with the pursuit of ISO 15189 accreditation in a public health laboratory in Ghana. PubMed. 2022.

Impact of accreditation on health care services performance in Kiryandongo district, Uganda: a longitudinal study. PMC. 2022. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8830999/

Quality matters in strengthening global laboratory medicine. PMC. 2016. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4956090/

Steindel SJ, et al. Reducing Laboratory Turnaround Time Outliers Can Reduce Emergency Department Patient Length of Stay: An 11-Hospital Study. ResearchGate. 2005.

Reducing Laboratory Turnaround Time Outliers Can Reduce Emergency Department Patient Length of Stay: An 11-Hospital Study. Am J Clin Pathol. 2005.

Reducing Laboratory Turnaround Time Outliers Can Reduce Emergency Department Patient Length of Stay: An 11-Hospital Study. ResearchGate. 2005.

Reduction in laboratory turnaround time decreases emergency room length of stay. PMC. 2018. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC5916382/

Reduction in laboratory turnaround time decreases emergency room length of stay. ResearchGate. 2018.

Slats AM, et al. Shorter laboratory turnaround time is associated with shorter emergency department length of stay: a retrospective cohort study. BMC Emerg Med. 2022;22:212.

Shorter laboratory turnaround time is associated with shorter emergency department length of stay: a retrospective cohort study. PMC. 2022. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9768765/

Shorter laboratory turnaround time is associated with shorter emergency department length of stay: a retrospective cohort study. PubMed. 2022.

Reduction in laboratory turnaround time decreases emergency room length of stay. PMC. 2018.

Reduction in laboratory turnaround time decreases emergency room length of stay. ResearchGate. 2018.

Shorter laboratory turnaround time is associated with shorter emergency department length of stay: a retrospective cohort study. BMC Emerg Med. 2022;22:212.

Revolutionizing the lab with AI in laboratory workflows. Roche Diagnostics Lab Leaders. 2025.

The role of artificial intelligence in diagnostics: A new frontier for laboratory medicine in Africa. Afr J Lab Med. 2025;14(1):2952.

The role of artificial intelligence in diagnostics: A new frontier for laboratory medicine in Africa. PMC. 2025. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC12505451/

Revolutionizing clinical laboratories: The impact of artificial intelligence in diagnostics and patient care. ScienceDirect. 2025.

The role of artificial intelligence in diagnostics: A new frontier for laboratory medicine in Africa. Afr J Lab Med. 2025.

Dodig S, Čepelak I, Dodig M. Are we ready to integrate advanced artificial intelligence models in clinical laboratory? Biochem Med (Zagreb). 2025;35(1):010501.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Dodig S, Čepelak I, Dodig M. Are we ready to integrate advanced artificial intelligence models in clinical laboratory? PMC. 2024. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11654238/

Giesriegl A, et al. How laboratory medicine will change in the near future: integrating artificial intelligence, automation, and human expertise in the era of Industry 5.0. J Lab Precis Med. 2025.

Miller HA, Valdes R. Rigorous validation of machine learning in laboratory medicine: guidance toward quality improvement. Crit Rev Clin Lab Sci. 2025;62:327-346.

Lennerz JK, Salgado R, Kim GE, et al. Diagnostic quality model (DQM): an integrated framework for the assessment of diagnostic quality when using AI/ML. Clin Chem Lab Med. 2023;61:544-557.