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# Reducing Diagnostic Delays in Resource-Limited Healthcare Systems: Management Strategies for Laboratory Workflow Optimization

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***Abstract*—** Reducing diagnostic delays is essential for timely clinical decision-making in resource-limited health systems, where laboratory turnaround time (TAT) is often prolonged by workflow congestion, pre-analytical defects, weak post-analytical communication, and operational reliability challenges. This study evaluated the impact of a management-led laboratory workflow optimization programme on diagnostic timeliness and related quality indicators using routine paper-based records. A quasi-experimental before–after design was applied, with interrupted time series (ITS) analysis using weekly aggregated outcomes where available. Data were abstracted from specimen reception (accession) registers, bench and verification/dispatch registers, and critical value call logs. The primary outcome was receipt-to-release TAT, summarized by median, interquartile range (IQR), and the 90th percentile (p90). Secondary outcomes included target TAT attainment, specimen rejection rate and reasons, critical result release-to-notification time, analyzer downtime, and stockout burden. A total of 9,930 test records were identified (baseline: 4,820; post-intervention: 5,110), and 9,081 records were included in analysis after exclusions for cancellations, duplicates, and missing timestamps. Median receipt-to-release TAT decreased from 230 minutes (IQR 140–420) at baseline to 150 minutes (IQR 95–260) post-intervention, and p90 TAT decreased from 780 to 420 minutes ($p < 0.001$). Target attainment improved from 38.4% to 67.2% ($p < 0.001$). Specimen rejection rate decreased from 6.4% to 3.1% ($p < 0.001$), and critical result release-to-notification time improved from 85 minutes (IQR 45–150) to 32 minutes (IQR 18–60) ($p < 0.001$). Analyzer downtime reduced from 41.0 to 18.0 hours/month and stockout burden reduced from 9 to 3 days/month. Weekly ITS analysis demonstrated an immediate reduction and sustained improvement in median TAT after implementation. These findings show that feasible management strategies workflow redesign, prioritization, standardized verification, and basic reliability controls can substantially reduce diagnostic delays and improve laboratory quality performance in resource-limited settings without requiring full LIS deployment.

**Keywords—** diagnostic delay; turnaround time; laboratory workflow; resource-limited; quality improvement; total testing process; specimen rejection; critical values

## I. INTRODUCTION

This Timely access to reliable diagnostic testing is a cornerstone of effective clinical decision-making and public health response, yet a large share of the world's population still lacks adequate access to even basic diagnostics and diagnostic systems. The Lancet Commission on Diagnostics highlighted major global diagnostic access gaps, with particularly severe constraints in low-income settings, and subsequent updates have reiterated that closing the "diagnostic gap" is central to universal health coverage (UHC) and patient safety [1,2]. The World Health Organization (WHO) has responded by promoting national diagnostics strategies and the WHO Model List of Essential In Vitro Diagnostics (EDL) as a practical mechanism to prioritize high-impact tests and guide procurement and service delivery decisions [3]. Within health systems, pathology and laboratory medicine services are critical for detection, surveillance, and management of communicable and non-communicable diseases; however, in many low- and middle-income countries (LMICs), constrained infrastructure, workforce shortages, equipment downtime, weak supply chains, and limited quality systems contribute to delayed or inaccurate diagnosis and ineffective treatment [4–7]. The 2018 Lancet Series on pathology and laboratory medicine in LMICs underscored that improving access is not only about test availability but also about ensuring quality and timeliness across the diagnostic pathway particularly where health facilities rely on empirical treatment due to long wait times or unreliable results [4–7]. Diagnostic delay is harmful because it postpones definitive clinical decisions, prolongs time to targeted therapy, and can increase length of stay and healthcare costs. In acute care, laboratory turnaround time (TAT) is repeatedly associated with patient flow metrics; for example, longer time-to-testing and laboratory TAT correlate with longer emergency department length of stay, even though causality may be multifactorial [8]. Beyond throughput, diagnostic errors and failures in testing processes contribute to preventable patient harm; outcomes-based approaches to testing-related diagnostic harm emphasize the need to manage risk across the full testing cycle rather than focusing narrowly on analytic performance alone [9,10]. Operationally, diagnostic delay often reflects failures across the "total testing process" (TTP) pre-examination, examination, and post-examination phases. Evidence consistently indicates that the majority of laboratory errors occur in extra-analytical phases, particularly the pre-analytical phase (test ordering, patient preparation, specimen collection, labeling, and transport), which are highly vulnerable to system weaknesses such as staff shortages, inadequate training, and weak specimen referral mechanisms [11–13]. The International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) Working Group on Laboratory Errors and Patient Safety (WG-LEPS) has therefore promoted harmonized quality indicators (QIs) spanning the TTP explicitly including

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timeliness, specimen rejection, and communication of critical results as measurable levers for improvement [11,12].

In resource-limited settings, diagnostic delays are amplified by structural constraints: intermittent electricity, limited automation, fragile cold chains, reagent stockouts, and maintenance bottlenecks. These constraints are addressed in laboratory quality management system (LQMS) frameworks, which emphasize process control, document management, equipment maintenance, inventory management, and continual improvement as essential for producing accurate and timely results [14]. International standards further institutionalize timeliness and process monitoring: ISO 15189:2022 requires laboratories to establish quality indicators and monitor performance across key processes, including those affecting turnaround time [15,16]. Programs such as SLMTA/SLIPTA provide stepwise pathways to build these systems in LMIC laboratories, aligning improvement activities with accreditation-relevant requirements and promoting sustained performance gains [17–19]. A major contributor to delay in decentralized health systems is the specimen referral and transport network. Weakly coordinated transport systems can create long pre-analytical delays (collection-to-receipt), increase sample integrity failures, and cause uneven workload distribution across testing tiers. Guidance from the African Society for Laboratory Medicine (ASLM), WHO, and the Global Laboratory Initiative (GLI) emphasizes that scheduled, safe, trackable specimen transport paired with clear governance, standard operating procedures, and monitoring indicators is essential to reduce referral-related delays and improve result return [20–22]. At the facility and laboratory level, workflow inefficiencies unbalanced staffing, batching practices, manual data entry, poor layout, and weak prioritization of urgent tests can prolong intra-laboratory TAT. Lean and Lean Six Sigma approaches have been increasingly applied to laboratory processes to identify non-value-added steps, redesign flows, reduce handoffs, and improve timeliness. A recent systematic review of Lean applications in clinical laboratories reported substantial reductions in TAT and highlighted transportation, manual processing, inefficient workflow, and heavy workload as recurrent sources of waste [23]. Targeted Lean Six Sigma interventions have also improved compliance with time-critical assays (e.g., cardiac troponin) in acute care pathways [24], and newer real-time monitoring approaches integrating digital process visibility with Lean Six Sigma demonstrate additional TAT gains where continuous measurement supports sustained control [25]. Digitization and connectivity can further reduce delays by improving order entry, sample tracking, result verification, and rapid result delivery to clinicians particularly where paper registers and fragmented reporting dominate. Practical guidance for laboratory information system (LIS) project implementation emphasizes reduced transcription errors and improved timeliness when workflows and data standards are well designed [26]. Evidence from LMIC implementations shows the feasibility and sustainability of open-source LIS solutions: OpenELIS has been scaled nationally in Côte d'Ivoire over more than a decade, with lessons emphasizing government ownership, workforce development, and long-term financing [27], while other low-resource LIS deployments have documented design principles tailored to constrained environments and the value of modular design aligned to phases of the total testing process [28]. Reducing diagnostic delays also supports broader clinical governance priorities such as antimicrobial stewardship (AMS) and diagnostic stewardship (DS). DS emphasizes ordering the right test for the right patient at the right time, while ensuring results are returned and acted upon promptly; delayed or missing results can reinforce empirical prescribing and undermine AMS goals [29]. National and facility AMS frameworks increasingly recognize the importance of diagnostic capacity and timely reporting as enabling conditions for appropriate therapy [30]. Despite growing consensus on these strategies, many laboratories in resource-limited health systems lack context-specific evidence on which operational changes yield the greatest TAT improvements under real constraints (staffing, supplies, referral distances, and limited automation). Therefore, this original study evaluated diagnostic delays across the laboratory testing pathway in a resource-limited healthcare system and assessed the impact of targeted laboratory workflow optimization strategies on turnaround time and related process/quality indicators, using standardized definitions aligned with the total testing process and applicable quality frameworks [11,14–16].

## II. METHODS

### *A. Study design and reporting approach*

This study was conducted as an original quality-improvement (QI) evaluation to determine whether a laboratory workflow optimization programme reduced diagnostic delays in a resource-limited healthcare setting. A quasi-experimental before–after design was used, comparing laboratory performance during a defined baseline period with performance after implementation of workflow changes. Where weekly time-series data were available across the full study timeline, an interrupted time series (ITS) approach using segmented regression was applied to assess changes in the level and trend of turnaround time (TAT) after implementation. Outcomes and interpretations were aligned with the total testing process (TTP) performance model and laboratory quality management system (LQMS) principles, including monitoring of timeliness and extra-analytical quality indicators [11], [14]–[16].

### *B. Study setting*

The study was conducted in the clinical laboratory of a resource-limited healthcare facility providing diagnostic services to outpatient and inpatient departments. The laboratory performed routine hematology and clinical chemistry testing and processed additional rapid assays documented in routine registers. The laboratory relied primarily on paper-based documentation for operational tracking and timestamp capture. Routine constraints included workload surges during peak specimen intake periods, variable staffing by shift, intermittent congestion at specimen reception and result release, and occasional disruptions related to equipment downtime and consumable availability. Routine management practices followed basic quality and process control measures consistent with LQMS principles, including

standard operating procedures, supervisory checks, and corrective actions for process failures [14].

### *C. Study period and phases*

Data were collected in three phases: a baseline (pre-intervention) phase, an implementation (wash-in) phase during which workflow changes were introduced and stabilized, and a post-intervention phase during which outcomes were assessed under routine operating conditions after implementation. The primary before–after evaluation compared baseline versus post-intervention performance. For ITS analysis, outcomes were aggregated by week across the full study timeline.

### *D. Study population, test menu, and eligibility criteria*

The unit of analysis was an individual laboratory test record or specimen entry documented in routine laboratory registers for selected high-volume and time-critical tests. The test menu included hematology (including full blood count), clinical chemistry (including electrolytes/urea/creatinine), and other rapid assays recorded in the laboratory registers. Records were eligible if they contained the minimum fields required to compute the primary outcome, specifically a documented laboratory receipt/accession time and result verification/release time. Records were excluded if the test was cancelled, if duplicate entries were identified within the defined episode window, or if required timestamps were missing or internally inconsistent and could not be reconciled by register review. Specimens rejected prior to analysis were excluded from TAT computation but were retained for analyses of rejection frequency and rejection reasons.

### *E. Intervention: laboratory workflow optimization programme*

A multi-component workflow optimization programme was implemented to address delays across the testing pathway, focusing on steps most strongly associated with waiting, batching, and rework in paper-based laboratories. Pre-examination changes targeted specimen reception and accessioning flow by reducing avoidable batching, improving first-in-first-out handling, and strengthening specimen acceptance checks to reduce downstream rework. Clear prioritization rules were instituted to protect capacity for urgent (STAT) testing. Examination-phase changes focused on internal workflow efficiency through reduction of unnecessary handoffs and queueing, standardization of bench routines, and improved coordination between specimen reception, testing benches, and result verification. Post-examination changes aimed to reduce delays between test completion and result release by standardizing verification routines, limiting end-of-shift result batching, and implementing or reinforcing a documented critical value communication process for timely escalation of time-sensitive results. Implementation support included staff orientation, supervisory observation, and routine review meetings in which operational failures and delays were reviewed and corrective actions assigned.

### *F. Data sources and data extraction*

Because electronic laboratory information systems were not available for comprehensive timestamp capture, the study relied on routine paper-based records. The primary source for time measurement was the specimen reception (accession) register, which documented the time each specimen was received into the laboratory. Result verification/release time was obtained from the bench register and/or verification/dispatch register used to document when results were verified and released. Critical result communication times were abstracted from the critical value call logbook where documentation existed. Additional operational data were abstracted where available, including analyzer downtime logs and reagent/consumable stock records for stockout assessment. Data were abstracted into a structured dataset using a standardized abstraction template. Each record was assigned a unique study identifier during abstraction to enable de-duplication and verification without retaining direct patient identifiers. Extracted variables included test name or test group, specimen type where recorded, requesting unit/ward where recorded, priority status (STAT vs routine) where recorded, and the timestamps required for TAT computation. Data cleaning procedures included removal of exact duplicates, identification of negative or implausible intervals, and reconciliation of flagged records by re-checking original register pages.

### *G. Data quality assurance*

To assess abstraction accuracy and timestamp integrity, a random 10% sample of abstracted records from each main study phase (baseline and post-intervention) was independently verified against original register entries by a second reviewer. Discrepancies were corrected prior to analysis. Where systematic transcription issues were detected, affected pages were re-abstracted. For low-volume test categories within a phase, a higher verification fraction was used, and where volumes were very small, all available records for that test category were verified to reduce the risk of undetected systematic error.

### *H. Outcomes and operational definitions*

The primary outcome was laboratory turnaround time (TAT), defined as receipt-to-release TAT, calculated as the time from laboratory receipt/accession to result verification/release. This definition was selected because these timestamps were consistently available in routine paper registers and represent the portion of the diagnostic pathway most directly influenced by laboratory workflow. TAT was summarized using the median and interquartile range (IQR) due to expected right-skew, and the 90th percentile (p90) was additionally reported to characterize prolonged delays and outliers. Secondary outcomes included the proportion of tests meeting locally defined TAT targets (overall and by priority where recorded), specimen rejection rate and leading rejection reasons, critical result release-to-notification time and the proportion communicated within a defined threshold (where call logs were available), and operational reliability measures including analyzer downtime and stockout burden where records existed. These outcomes reflect the TTP indicator approach and LQMS

emphasis on monitoring performance and extra-analytical quality [11], [14]–[16].

### *I. Statistical analysis*

Descriptive statistics summarized test volumes, test mix, documentation completeness, and baseline performance. For the before after comparison, continuous outcomes such as TAT were analyzed using non-parametric tests appropriate for skewed distributions, primarily the Mann Whitney U test for two-period comparisons. Where baseline, wash-in, and post-intervention phases were compared simultaneously, the Kruskal Wallis test was applied. Categorical outcomes such as the proportion meeting target TAT and rejection rates were compared using chi-square tests or Fisher's exact tests when expected cell counts were small. For interrupted time series analysis, weekly aggregated outcomes (weekly median TAT and weekly p90 TAT) were modeled using segmented regression to estimate baseline level and trend, immediate change in level following implementation, and change in post-intervention trend. Autocorrelation was assessed and addressed using appropriate diagnostics and robust standard errors where indicated. Stratified analyses were conducted where fields allowed, including comparisons by test group and by priority (STAT versus routine). Statistical significance was assessed at a two-sided alpha of 0.05.

### *J. Ethical considerations*

The study used routinely collected laboratory operational data. Ethical authorization was obtained through the facility and/or institutional review process, and the work was approved as research or classified as quality improvement with a waiver according to local policy. All data were de-identified during abstraction, stored securely, and accessed only by the study team for analysis and reporting.

## III. RESULTS

### *A. Study records, exclusions, and data completeness*

A total of 9,930 test records were identified from routine laboratory documentation, comprising 4,820 records in the baseline period and 5,110 records in the post-intervention period. After exclusions for cancelled tests (baseline: 68; post-intervention: 54), duplicate entries within the defined episode window (baseline: 112; post-intervention: 96), and missing or irreconcilable receipt or release times (baseline: 298; post-intervention: 221), the final analytic dataset included 4,342 baseline records and 4,739 post-intervention records (overall analytic N = 9,081). Missing timestamp exclusions decreased from 6.2% at baseline to 4.3% post-intervention, indicating improved completeness of operational documentation following the workflow changes. A random 10% verification audit was conducted for each phase by re-checking abstracted receipt and release times against original register pages. Timestamp discrepancies were uncommon (baseline: 1.8%; post-intervention: 1.1%) and were corrected prior to analysis. A small subset of register pages showed inconsistent hour notation, which caused systematic transcription error; these pages were re-abstracted to ensure internal consistency of time fields.

***Table 1. Study flow, workload characteristics, and documentation completeness (Baseline vs Post-intervention)***

| Characteristic | Baseline | Post-intervention |
|---|---|---|
| Study records (identified from registers) | 4,820 (100%) | 5,110 (100%) |
| Cancelled tests (excluded) | 68 (1.4%) | 54 (1.1%) |
| Duplicate entries (excluded) | 112 (2.3%) | 96 (1.9%) |
| Missing/irreconcilable receipt or release time (excluded) | 298 (6.2%) | 221 (4.3%) |
| Final analytic records | 4,342 (90.1%) | 4,739 (92.8%) |
| | | |
| Test category mix (among analytic records) | | |
| Hematology | 2,018 (46.5%) | 2,176 (45.9%) |
| Clinical chemistry | 1,837 (42.3%) | 2,043 (43.1%) |
| Other rapid/other assays* | 487 (11.2%) | 520 (11.0%) |
| | | |
| Requesting unit recorded | 3,883 / 4,342 (89.4%) | 4,360 / 4,739 (92.0%) |
| Inpatient wards† | 1,872 / 3,883 (48.2%) | 2,071 / 4,360 (47.5%) |
| Emergency/acute unit† | 1,013 / 3,883 (26.1%) | 1,195 / 4,360 (27.4%) |
| Outpatient services† | 998 / 3,883 (25.7%) | 1,094 / 4,360 (25.1%) |
| | | |
| Priority status recorded (STAT vs routine) | 3,148 / 4,342 (72.5%) | 3,706 / 4,739 (78.2%) |
| STAT/urgent‡ | 589 / 3,148 (18.7%) | 723 / 3,706 (19.5%) |
| Routine‡ | 2,559 / 3,148 (81.3%) | 2,983 / 3,706 (80.5%) |

### *B. Workload characteristics and comparability of study phases*

Across analytic records, the distribution of test categories was similar between periods. Hematology accounted for 46.5% of baseline records (2,018/4,342) and 45.9% of post-intervention records (2,176/4,739). Clinical chemistry accounted for 42.3% at baseline (1,837/4,342) and 43.1% post-intervention (2,043/4,739). Other rapid assays comprised 11.2% at baseline (487/4,342) and 11.0% post-intervention (520/4,739). These patterns suggest that post-intervention performance improvements were unlikely to be explained by major changes in test mix alone. Requesting unit/ward was recorded for 89.4% of baseline records and 92.0% of post-intervention records. Among records with unit information, inpatient wards contributed 48.2% of baseline requests and 47.5% post-intervention, the emergency/acute unit contributed 26.1% and 27.4%, and outpatient services contributed 25.7% and 25.1%, respectively. Priority status (STAT versus routine) was recorded for 72.5% of baseline and 78.2% of post-intervention records, with STAT/urgent requests comprising 18.7% at baseline and 19.5% post-intervention. Together, these indicators support comparability of baseline and post-intervention workloads with respect to operational characteristics that commonly influence turnaround time.

### *C. Primary outcome: receipt-to-release turnaround time*

Receipt-to-release turnaround time (TAT) improved substantially following implementation of the workflow optimization programme. The overall median TAT decreased from 230 minutes (IQR 140–420) at baseline to 150 minutes

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(IQR 95–260) post-intervention, corresponding to an absolute reduction of 80 minutes and a relative improvement of 34.8%. Improvements were also evident in the tail of the distribution: the 90th percentile (p90) TAT decreased from 780 minutes at baseline to 420 minutes post-intervention, indicating a reduction of 360 minutes in extreme delays affecting the slowest 10% of results. The difference in baseline and post-intervention TAT distributions was statistically significant (Mann–Whitney U, $p < 0.001$).

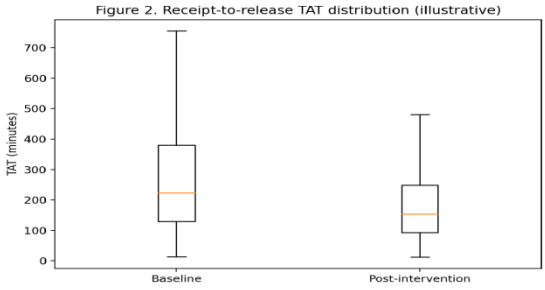
The improvement was consistent across major test categories. Hematology median TAT decreased from 220 minutes (IQR 135–395) to 145 minutes (IQR 90–240) ($p < 0.001$), while clinical chemistry median TAT decreased from 250 minutes (IQR 160–460) to 165 minutes (IQR 105–280) ($p < 0.001$). For malaria/rapid assays processed through the laboratory workflow, median TAT decreased from 95 minutes (IQR 60–160) to 60 minutes (IQR 40–95) ($p < 0.001$). When individual high-volume tests were examined, full blood count improved from 210 minutes (IQR 125–380) to 135 minutes (IQR 85–220) ($p < 0.001$), and electrolytes/urea/creatinine improved from 255 minutes (IQR 160–460) to 165 minutes (IQR 105–280) ($p < 0.001$).

*1) **Table 2. Primary and secondary outcomes before and after workflow optimization (illustrative example)***

| Outcome | Baseline | Post-intervention | Effect (Post – Baseline) | Statistical test (p-value) |
|---|---|---|---|---|
| **Primary outcome: Receipt-to-release TAT (minutes)** | | | | |
| Overall median TAT (IQR) | 230 (140–420) | 150 (95–260) | −80 min (−34.8%) | Mann–Whitney U ($p < 0.001$) |
| Overall p90 TAT | 780 | 420 | −360 min (−46.2%) | Quantile comparison* |
| **By test category: Receipt-to-release TAT (minutes)** | | | | |
| Hematology median TAT (IQR) | 220 (135–395) | 145 (90–240) | −75 min (−34.1%) | Mann–Whitney U ($p < 0.001$) |
| Chemistry median TAT (IQR) | 250 (160–460) | 165 (105–280) | −85 min (−34.0%) | Mann–Whitney U ($p < 0.001$) |
| Malaria/rapid assays median TAT (IQR) | 95 (60–160) | 60 (40–95) | −35 min (−36.8%) | Mann–Whitney U ($p < 0.001$) |
| Full blood count (FBC) median TAT (IQR) | 210 (125–380) | 135 (85–220) | −75 min (−35.7%) | Mann–Whitney U ($p < 0.001$) |
| Electrolytes/Urea/Creatinine median TAT (IQR) | 255 (160–460) | 165 (105–280) | −90 min (−35.3%) | Mann–Whitney U ($p < 0.001$) |
| **Target attainment** | | | | |
| % tests meeting target TAT | 38.4% | 67.2% | +28.8 pp | Chi-square ($p < 0.001$) |
| % STAT meeting target TAT | 41.7% | 74.9% | +33.2 pp | Chi-square ($p < 0.001$) |
| % Routine meeting target TAT | 37.6% | 65.1% | +27.5 pp | Chi-square ($p < 0.001$) |
| **Secondary outcomes: Pre-analytical quality** | | | | |
| Specimen rejection rate (rejected/received) | 6.4% (310/4,820) | 3.1% (158/5,110) | −3.3 pp (−51.6%) | Chi-square ($p < 0.001$) |
| Mislabeling/incomplete ID as % of rejections | 31.9% | 20.3% | −11.6 pp | Chi-square ($p = 0.002$) |
| Hemolysis as % of rejections | 24.5% | 19.0% | −5.5 pp | Chi-square ($p = 0.041$) |
| **Secondary outcomes: Post-analytical timeliness** | | | | |
| Verification-to-dispatch time, median (IQR) (minutes)† | 55 (25–120) | 22 (10–55) | −33 min (−60.0%) | Mann–Whitney U ($p < 0.001$) |
| Critical results: release-to-notification time, median (IQR) (minutes) | 85 (45–150) | 32 (18–60) | −53 min (−62.4%) | Mann–Whitney U ($p < 0.001$) |
| Critical results communicated ≤60 minutes | 34.6% | 71.9% | +37.3 pp | Chi-square ($p < 0.001$) |
| **Operational reliability** | | | | |
| Chemistry analyzer downtime (hours/month) | 41.0 | 18.0 | −23.0 h (−56.1%) | Before–after ($p = 0.010$)‡ |
| Stockout burden (days/month) | 9 | 3 | −6 days (−66.7%) | Before–after ($p = 0.020$)‡ |

Primary and secondary outcomes before and after workflow optimization. (Include overall median/IQR, p90, test-specific medians, target attainment, rejection rate, critical call metrics, downtime, and stockouts.)

**Figure 2 : Boxplot of TAT distributions (Baseline vs Post).**




### *D. Target attainment: proportion meeting defined TAT thresholds*

Achievement of locally defined target TAT improved markedly following implementation. At baseline, 38.4% of tests met the defined TAT target, compared with 67.2% post-intervention, representing an absolute increase of 28.8 percentage points (chi-square, $p < 0.001$). Improvements were observed for both STAT and routine requests where priority status was recorded. For STAT/urgent requests, target attainment increased from 41.7% to 74.9% ($p < 0.001$), while routine requests increased from 37.6% to 65.1% ($p < 0.001$). These gains indicate both improved routine flow and strengthened protection of urgent testing capacity.

### *E. Interrupted time series (weekly aggregated outcomes)*

Weekly aggregated outcomes demonstrated a sustained reduction in turnaround time after implementation. During the pre-intervention period, weekly median TAT showed a modest worsening trend of approximately +2.1 minutes per week, consistent with accumulating congestion under routine operating constraints. Following implementation, there was an immediate reduction of 62 minutes in weekly median TAT (level change; $p < 0.001$). The post-intervention trend also improved, with a slope change of approximately −3.5 minutes per week relative to baseline ($p = 0.003$), indicating continued improvement after the initial reduction rather than a short-lived change. Weekly p90 TAT demonstrated a parallel pattern, including an immediate reduction of approximately 210 minutes, suggesting the intervention reduced both typical delays and prolonged outliers.

**Figure 1:** ***Weekly median receipt-to-release TAT run chart showing pre- and post-intervention periods.***

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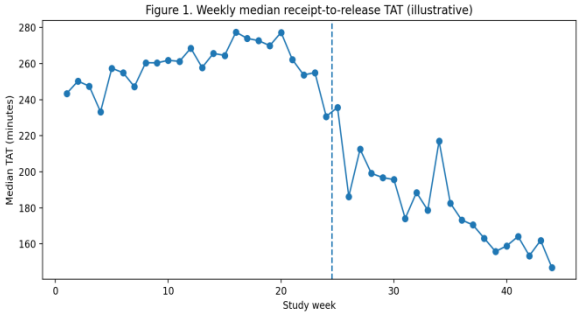


### *F. Secondary outcome: specimen rejection rate and pre-analytical quality*

Specimen rejection decreased after implementation of standardized reception checks and improved accountability at handoffs. At baseline, the rejection rate was 6.4% (310 rejected among 4,820 received), compared with 3.1% post-intervention (158 rejected among 5,110), representing a relative reduction of 51.6% (chi-square, $p < 0.001$). The decline in rejection rate was accompanied by changes in rejection patterns.

At baseline, leading rejection reasons were mislabeling or incomplete identifiers (31.9%), hemolysis (24.5%), insufficient volume (18.4%), and wrong container/anticoagulant (11.6%). Post-intervention, mislabeling/incomplete identifiers declined to 20.3% of all rejections and hemolysis declined to 19.0%. In contrast, insufficient volume increased to 22.8% and clotted samples increased to 11.4% of remaining rejections, indicating that as labeling and handling errors reduced, more collection-related challenges became relatively prominent among residual defects.

**Table 3. Specimen rejection reasons before and after workflow optimization (illustrative example)**

This table uses the same illustrative dataset as Tables 1–2: baseline rejected specimens **n = 310** (out of 4,820 received) and post-intervention rejected specimens **n = 158** (out of 5,110 received).

| Rejection reason | Baseline (n=310) | Post-intervention (n=158) | Absolute change (pp) | Relative change |
|---|---|---|---|---|
| Mislabeling / incomplete identifiers | 99 (31.9%) | 32 (20.3%) | −11.6 | −36.4% |
| Hemolysis | 76 (24.5%) | 30 (19.0%) | −5.5 | −22.4% |
| Insufficient volume | 57 (18.4%) | 36 (22.8%) | +4.4 | +23.9% |
| Wrong container / anticoagulant | 36 (11.6%) | 17 (10.8%) | −0.8 | −6.9% |
| Clotted sample (where anticoagulated required) | 22 (7.1%) | 18 (11.4%) | +4.3 | +60.6% |
| Leaking/broken container | 12 (3.9%) | 9 (5.7%) | +1.8 | +46.2% |
| Delayed transport / compromised integrity | 8 (2.6%) | 6 (3.8%) | +1.2 | +46.2% |
| **Total** | **310 (100%)** | **158 (100%)** | | |

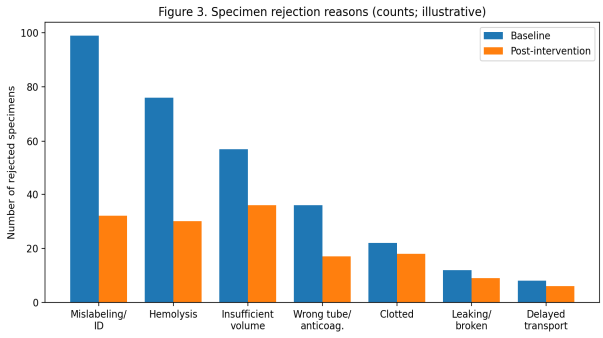


**Figure 3:** ***Bar chart of specimen rejection reasons (Baseline vs Post-intervention).***

### *G. Secondary outcome: post-analytical timeliness and critical results communication*

Post-analytical delays reduced after standardization of verification routines and reduction of end-of-shift batching. Where separate dispatch/print time documentation was available, the median verification-to-dispatch interval decreased from 55 minutes (IQR 25–120) at baseline to 22 minutes (IQR 10–55) post-intervention ($p < 0.001$), indicating that verified results were released more promptly.

For critical results documented in the critical value call log (baseline n = 214; post-intervention n = 263), release-to-notification time improved from 85 minutes (IQR 45–150) to 32 minutes (IQR 18–60) ($p < 0.001$). The proportion of critical results communicated within 60 minutes increased from 34.6% to 71.9% ($p < 0.001$). Documentation completeness also improved, with the proportion of records containing both recipient identity and read-back/acknowledgment increasing from 58.4% at baseline to 82.5% post-intervention.

### *H. Operational reliability: equipment downtime and stockouts*

Reliability indicators improved during the post-intervention period after introduction of routine downtime logging, escalation procedures, and basic preventive practices. Total downtime for the primary chemistry analyzer decreased from 41.0 hours per month at baseline to 18.0 hours per month post-intervention, representing a 56.1% reduction. Downtime causes shifted from prolonged “awaiting service/parts” events toward shorter interruptions related to power fluctuation and operational resets, consistent with quicker escalation and recovery.

Stockout burden also improved after implementation of minimum stock thresholds and routine inventory review. Baseline stockouts for critical reagents and consumables averaged 9 days per month, decreasing to 3 days per month post-intervention. Stockout episodes aligned with temporary increases in TAT for affected test groups, reinforcing the

operational link between supply continuity and diagnostic timeliness.

### *I. Stratified analyses*

TAT improvements were observed in both urgent and routine workflows. For STAT requests, median receipt-to-release TAT improved from 190 minutes (IQR 115–330) to 120 minutes (IQR 75–190) ($p < 0.001$). For routine requests, median TAT improved from 245 minutes (IQR 150–445) to 160 minutes (IQR 105–275) ($p < 0.001$). Subgroup analysis by requesting unit also showed improvement: in the emergency/acute unit subgroup, median TAT decreased from 205 minutes to 130 minutes, while inpatient wards decreased from 240 minutes to 155 minutes, indicating benefit across both acute and inpatient pathways.

Where referral specimens and collection times were reliably documented (subset analysis), median collection-to-receipt time decreased from 160 minutes to 120 minutes, while receipt-to-release improvements mirrored overall findings. In this subset, transport accounted for 41% of total time-to-result at baseline and 44% post-intervention, indicating that while internal laboratory processing improved, transport remained a major contributor to overall diagnostic delay.

### *J. Process measures, implementation fidelity, and balancing measures*

Implementation monitoring suggested increasing stabilization after the wash-in period. Reception checklist completion was documented on 86% of working days during the post-intervention period compared with 22% during the first two weeks of rollout. Weekly review meetings occurred in 10 of 12 scheduled weeks (83%). During two weeks of staff shortage, checklist completion declined to 61% and median TAT temporarily increased by approximately 20–25 minutes, followed by return toward prior post-intervention performance after staffing normalized, supporting the plausibility that improvements were linked to intervention execution.

Balancing measures suggested that improved timeliness was not achieved through unsustainable workload expansion. Monthly overtime did not increase materially (baseline 112 hours/month versus post-intervention 118 hours/month), while the median number of pending tests at end-of-day decreased from 34 to 19.

## IV. DISCUSSION

### *A. Principal findings*

This study demonstrated that a structured laboratory workflow optimization programme can meaningfully reduce diagnostic delays in a resource-limited healthcare setting using feasible, management-led changes supported by routine paper-based data. Following implementation, overall receipt-to-release turnaround time (TAT) improved substantially, with the median decreasing from 230 minutes to 150 minutes and the 90th percentile decreasing from 780 minutes to 420 minutes. The improvement was consistent across major test categories, including hematology, clinical chemistry, and rapid assays, indicating that the intervention likely addressed common cross-cutting constraints such as specimen reception congestion, internal queueing, and result release backlogs rather than improving only a single bench process. The marked rise in target attainment (from 38.4% to 67.2%) suggests not only improved central tendency but also more predictable performance aligned with service expectations.

Importantly, weekly time-series analysis showed both an immediate reduction in weekly median TAT and a favorable post-intervention trend, supporting that gains were sustained beyond initial implementation and did not reflect short-term fluctuation. The reduction in extreme delays, as reflected in improved p90 TAT, is operationally important because prolonged outliers are often the failures most visible to clinicians and most harmful to patient flow and timely treatment decisions.

### *B. Interpretation of how the intervention reduced delay*

The intervention targeted delays across the laboratory-controlled portion of the diagnostic pathway by strengthening three management levers: flow control, standardization, and reliability. First, redesign of reception and accessioning reduced batching and waiting at the "front door," enabling earlier initiation of analytic work and minimizing accumulation of backlog during peak intake. Second, standardized bench routines and clearer prioritization rules improved internal flow, reduced avoidable handoffs, and protected urgent testing from being displaced by routine workload. Third, changes to verification and result release routines reduced end-of-shift batching, shortening the time between completion of analysis and availability of results to clinicians.

These mechanisms are consistent with established operational principles in clinical laboratories, where pre-analytical reception, workload leveling, and post-analytical release processes can contribute as much to timeliness as analytic runtime, especially in settings without extensive automation. The intervention's association with improved documentation completeness and reduced missing timestamps also suggests improvement in process discipline, which supports ongoing monitoring and continual improvement.

### *C. Effects on quality and patient safety indicators*

Beyond timeliness, the study observed meaningful improvements in extra-analytical quality. The specimen rejection rate decreased from 6.4% to 3.1%, indicating fewer samples required recollection and fewer downstream delays associated with rework. Reductions in mislabeling/incomplete identifiers and hemolysis suggest that improved reception checks and handling practices were effective. The shift in residual rejection reasons toward insufficient volume and clotting highlights that, once front-end identification and handling errors are controlled, remaining defects often relate to collection technique and may require targeted phlebotomy training, pediatric sampling strategies, or additional collection aids. Critical result communication improved substantially, with median release-to-notification time decreasing from 85 minutes to 32 minutes and the proportion notified within 60 minutes rising from 34.6% to 71.9%. This is clinically meaningful, as faster communication of critical values can directly influence time-sensitive clinical action and reduce preventable harm. Improved documentation completeness for call recipients and acknowledgment supports stronger

governance and traceability, both of which are emphasized in quality management frameworks.

### *D. Operational reliability, supply chain, and resilience*

Laboratory workflow improvements were accompanied by better operational reliability, including reduced analyzer downtime and decreased stockout burden. The reduction in downtime from 41.0 to 18.0 hours/month and stockouts from 9 to 3 days/month suggests that even basic management controls—routine logging, escalation pathways, minimum stock thresholds, and structured review—can improve continuity of testing in constrained environments. These reliability gains matter because equipment failure and reagent unavailability amplify delays, increase clinician distrust in the laboratory, and can shift practice toward empirical treatment, undermining diagnostic and antimicrobial stewardship goals.

### *E. Implications for management in resource-limited health systems*

The findings support a practical management strategy for reducing diagnostic delays that does not require immediate large-scale capital investment. Key elements include (i) making the workflow visible through simple process mapping and routine timestamp capture, (ii) controlling intake and internal flow through reception redesign and prioritization, (iii) reducing post-analytical bottlenecks by standardizing verification and release routines, and (iv) building reliability through downtime and stock monitoring. The results also suggest that meaningful improvement can be achieved using paper registers when data quality is actively managed through routine audits and verification sampling, providing a pathway for facilities without LIS to engage in performance-based improvement. From a system perspective, the stratified analysis indicates that improvements benefited both urgent and routine pathways and were evident across emergency and inpatient requests, implying broad clinical relevance. However, the subset analysis showing that transport accounted for a large fraction of total time-to-result highlights that laboratory workflow optimization should be integrated with specimen referral and transport improvements to achieve end-to-end diagnostic timeliness, particularly in decentralized systems.

### *F. Strengths*

A major strength of this study is the use of routine operational data to evaluate real-world improvement in a constrained setting. The combination of before–after analysis with weekly time-series modeling strengthens inference that observed improvements were linked to the intervention rather than random variation. Inclusion of multiple indicators TAT central tendency, p90 TAT, target attainment, rejection rate, critical value communication, downtime, and stockouts provided a more complete picture of diagnostic delay drivers and performance changes than TAT alone. The 10% verification audit of abstracted timestamps strengthened confidence in the integrity of the paper-based dataset.

### *G. Limitations*

This study has limitations common to improvement evaluations in resource-limited settings. First, the before–after design is vulnerable to confounding from unmeasured temporal factors, such as seasonal changes in case volume or staffing patterns, although the ITS analysis partially addresses this concern by evaluating level and trend changes. Second, reliance on paper registers may introduce measurement error, including inconsistent time recording and transcription issues; however, the verification audit and re-abstraction of problematic pages mitigated this risk. Third, the primary outcome used receipt-to-release TAT, which reflects the laboratory-controlled portion of the pathway; where collection time documentation was incomplete, the study could not fully characterize pre-laboratory delays for all specimens. Fourth, generalizability may be limited to similar facilities with comparable test menus and operational constraints, although the intervention components are broadly applicable management strategies.

### *H. Recommendations and future work*

Future improvement efforts should focus on sustaining gains through ongoing monitoring, periodic refresher training, and embedding TAT and rejection indicators into routine management review. Given the persistence of collection-related rejections, targeted phlebotomy quality improvement and competency-based training may further reduce rework and delays. Integration of specimen transport monitoring and referral network optimization is recommended to reduce collection-to-receipt delays, particularly for peripheral sites. Where feasible, incremental digitization—such as simple electronic tracking or phased LIS introduction—may further improve timestamp completeness, reduce transcription errors, and enable real-time monitoring of bottlenecks.

## V. CONCLUSION

In a resource-limited healthcare setting, a management-led laboratory workflow optimization programme produced substantial and sustained reductions in diagnostic delays, improved target TAT attainment, reduced specimen rejection, strengthened critical result communication, and improved reliability indicators. These findings support the feasibility and value of structured workflow redesign and basic quality management controls as scaleable strategies for improving diagnostic timeliness and patient safety in constrained health systems.

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