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ORIGINAL ARTICLE

Improving the Workflow of Hematology and Coagulation Workstations Using a Total Laboratory Automation System

Chen-Yu Lee [1, *], Jiunn-Min Wang [2, *], Ming-Tze Yang [1]

[*] *These authors contributed equally to this work as co-first authors*
[1] *Department of Pathology and Laboratory Medicine, Taichung Veterans General Hospital, Taiwan*
[2] *Department of Laboratory Medicine, Taichung Tzu Chi Hospital, Buddhist Tzu Chi Medical Foundation, Taichung, Taiwan*

ABSTRACT

Background: **Total Laboratory Automation (TLA) integrates pre-analytical, analytical and post-analytical processes into a seamless workflow, improving efficiency, reducing errors, and enhancing diagnostic accuracy. Despite its advantages, comprehensive TLA integration in hematology and coagulation laboratories remains challenging due to complex sample handling and instrument-specific requirements. This study evaluates the impact of TLA implementation on workflow efficiency and turnaround time (TAT) in a high-volume clinical laboratory.**
Methods: **This study was conducted at Taichung Veterans General Hospital (VGHTC). Since October 2023, the laboratory has integrated hematology and coagulation analyzers with an Abbott GLP SYSTEMS TRACK.**
Results: **The integration of TLA significantly improved workflow efficiency and reduced operational costs. TAT compliance rates for hematology and coagulation testing improved from 82.0% and 76.9% to 95.2% and 93.0%, respectively, one year after implementation. Monthly blood collection tube consumption decreased by 2,915 units, resulting in cost savings of $437 USD and reducing carbon emissions by 32 kg CO2e. The automation system eliminated manual specimen transport requirements, saving one full-time equivalent staff position.**
Conclusions: **Implementing TLA in hematology and coagulation testing enhances operational efficiency, reduces environmental impact, and improves diagnostic turnaround time. Future studies should focus on long-term sustainability and clinical outcomes associated with laboratory automation.**
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Correspondence:
Ming-Tze Yang, MS
1650 Taiwan Boulevard Sect. 4
Taichung, 40705, ROC
Taiwan
Phone: +886 423592525 ext. 4517
Fax: +886 423741267
Email: ming75@vghtc.gov.tw

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INTRODUCTION

Total Laboratory Automation (TLA) systems integrate multiple processes - pre-analytical, analytical, and post-analytical - into a unified automated system [1-3]. This integration enables seamless sample transportation, processing, and analysis through a centralized track system. By eliminating numerous manual tasks, TLA enhances operational efficiency, minimizes human error, and ensures more consistent and reliable laboratory results. Additionally, TLA systems can handle high volumes of

specimens, significantly reducing turnaround time (TAT), which is particularly critical for urgent clinical decision-making. These systems also contribute to optimal resource allocation by streamlining the utilization of laboratory personnel, space, and equipment, thereby improving overall productivity and supporting high-quality patient care [4].

In most clinical laboratories in Taiwan, partial automation is commonly implemented, such that hematology and coagulation analyzers are not connected with the automation system [5]. Hematology testing, particularly complete blood count (CBC) analysis, involves complexities that can strain TLA systems. While the majority of CBC specimens can be processed via automated analyzers, specific specimens may require manual microscopic examination, such as peripheral blood smears for morphological assessment. Further complicating TLA integration is the requirement for reflex testing in response to abnormal results, as these procedures frequently demand specialized handling protocols and additional processing time.

Similarly, coagulation testing, which encompasses assays such as prothrombin time (PT) and activated partial thromboplastin time (aPTT), presents pre-analytical and analytical challenges when integrated with TLA [6-8]. Coagulation assays exhibit high sensitivity to factors including sample integrity, centrifugation protocols, and reagent stability. Processing delays or suboptimal sample conditions can compromise test results, potentially leading to erroneous diagnostic interpretations. Additionally, coagulation analyzers typically require specific maintenance procedures and reagent preparation methods that may not integrate efficiently with TLA workflows. Moreover, the considerable variation in sample types and patient conditions from low-volume neonatal specimens to samples from anticoagulated patients creates significant challenges for automated systems to maintain consistent accuracy and reliability [9]. To overcome these challenges, laboratories have collaborated extensively with TLA vendors and analyzer manufacturers to develop customized workflows that preserve sample integrity throughout the automation process.

The integration of TLA systems in both hematology and coagulation testing continues to evolve, with ongoing technological and procedural advancements specifically designed to optimize diagnostic efficiency and improve patient outcomes. These developments focus on resolving interface challenges between specialized analyzers and automation tracks while maintaining analytical precision across diverse specimen types and clinical scenarios. The successful implementation of TLA in hematology and coagulation laboratories necessitates a meticulously balanced approach that harmonizes technological innovation with specialized clinical expertise. In the literature, several studies have reported successful implementation of TLA. A study demonstrated a significant reduction in turnaround time for CBC results when integrating the Sysmex analyzer with an advanced TLA system [10]. These efforts have resulted in improved operational efficiency and diagnostic accuracy, as highlighted in the study by Yu et al., which demonstrated how automation in coagulation laboratories led to a reduction in turnaround times and increased overall throughput without compromising test accuracy [11]. A study conducted by Giorgio et al. showed that an automation system can improve the quality control of coagulation assays by reducing human error and specimen misidentification, leading to more accurate and reliable results [12].

By addressing and overcoming the unique challenges associated with CBC and coagulation testing, laboratories can fully leverage the benefits of TLA to improve diagnostic accuracy and patient outcomes. In our laboratory, we have successfully integrated hematology and coagulation analyzers with a TLA system. As part of this initiative, we aimed to assess the impact of this integration on testing workflows and reporting efficiency, focusing on the operational differences observed before and after the connection to the TLA system.

MATERIALS AND METHODS

Data availability statement

Those data were recorded with intelligent information system (from January 1, 2023 to December 31, 2024). The data meet the criteria for exemption from the Institutional Review Board (IRB) of Taichung Veterans General Hospital, Taiwan (Exemption No. CW25333B).

Study site

This study was conducted at Taichung Veterans General Hospital (VGHTC), a 1,634-bed tertiary medical center that handles approximately 9,300 outpatient visits and 200 emergency room patients daily. The hospital's core laboratory processes over 9,768,035 million specimens per year.

Total laboratory automation (TLA) system

The laboratory implemented the Abbott GLP SYSTEMS TRACK (Abbott, IL, USA), integrating hematology and coagulation analyzers into a unified workflow. The system included two input/output modules (IOM), two bulk loader modules (BLM), one tube assessment center (TAC), four centrifuge modules (CM), two decapper modules (DM), one aliquot module (AM), three buffer modules (BM), two recapper modules (RM), three archive II modules, one remover module (REM), and one rack builder module (RBM). The instruments integrated with the TLA system included four Abbott chemistry analyzers, four Abbott immunology analyzers, one Abbott HbA1c analyzer, one Sysmex XN-9100 hematology system, and one Sysmex CS-5100 coagulation analyzer.

The TUNYEN laboratory information system (LIS)

We utilized the TUNYEN Laboratory Information System (LIS) specimen tracking system to monitor and analyze the workflow of samples from collection to test completion, enabling comprehensive assessment of process efficiency and management of abnormal specimens. This system provides real-time tracking of outpatient and inpatient samples, displaying their status across various stages, including sample collection login, TLA emergency inspection processing, and subsequent testing and reporting, with timelines indicating expected and actual processing times. The system records sample source, specimen number, medical record number, turnaround time (TAT), workstation, sampling location, arrival time, and test items, while also tracking the current status, such as "pending review" or "in progress." Additionally, abnormal specimens are highlighted to ensure timely handling of special or delayed samples. This system enables statistical analysis of sample workflow data, evaluates TAT compliance, and identifies potential bottlenecks affecting turnaround times, ultimately optimizing hematology and other laboratory testing processes.

Turnaround time (TAT) assessment before and after TLA implementation

We conducted a retrospective analysis of TAT at the hematology and coagulation workstation before and after the implementation of total laboratory automation to evaluate its impact on efficiency. Sample data were collected from January 2023 to December 2024, with TAT defined as the time from sample receipt to result verification and categorized into different thresholds (60 minutes, 90 minutes, 120 minutes, 150 minutes, 180 minutes, and 210 minutes). The study was divided into two phases: Pre-TLA implementation (January to October 2023) and post-TLA implementation (November 2023 to December 2024), with October 2023 serving as the transition reference point. The proportion of samples meeting each TAT criterion was analyzed monthly and visualized using stacked bar charts. We compared the proportion of samples achieving the 60-minute TAT benchmark pre- and post-TLA implementation and assessed the reduction in delayed samples (above 90 minutes) to quantify the impact of TLA. Ultimately, the improvement in TAT achievement rates was used to determine the efficiency enhancement of the hematology and coagulation workstation after TLA implementation, and statistical analyses were performed to verify the significance of these changes.

Statistics

All variables were compared using the Student's *t*-test. A p-value of < 0.05 was considered statistically significant.

RESULTS

Total laboratory automation (TLA) layout

Figure 1 illustrates the finalized layout of the total laboratory automation (TLA) system implemented in our laboratory. The system was designed to support high-throughput testing while optimizing sample flow and minimizing manual intervention. To accommodate specimens from multiple collection sources and prevent congestion at a single entry point, two input/output modules (IOMs) were installed at the specimen reception area. Area A represents the hematology workstation, where a Sysmex XN-9100 hematology analyzer is directly connected to the TLA system. Area B corresponds to the coagulation workstation, which includes two Sysmex CS-5100 coagulation analyzers. Area C houses the cold storage unit, which provides temperature-controlled temporary storage for delayed or special-processing samples. Based on workload or specific test requirements, samples can be dynamically rerouted to or retrieved from this unit. Automated centrifugation is performed in Area D, which contains four integrated centrifuges configured with a standardized setting of 3,136 x g for 10 minutes, accommodating a variety of specimen types under a unified protocol. The main analytical zones - Areas C, D, and E - include chemistry, immunology, and other specialty analyzers. These instruments are interconnected by an automated track system that ensures seamless and efficient specimen transport. The system's configuration allows for precise routing of specimens to designated analyzers and rerouting for archiving or additional testing when necessary.

Implementation of a real-time specimen tracking monitor system

To enhance workflow transparency and strengthen process control, a real-time specimen tracking monitor system was deployed in conjunction with the TLA implementation. As illustrated in Figure 2, this system provides end-to-end visibility of each specimen's status across all processing stages - from check-in, blood collection, and log-in, through to analysis and post-processing. The system dashboard delivers real-time updates on the number of specimens at each workflow step and automatically flags abnormal or delayed samples in red to prompt immediate attention. It also distinguishes between patient categories (e.g., outpatient and inpatient), allowing laboratories to monitor multiple processing streams independently via parallel progress bars. Beyond visual tracking, the system records provide detailed metadata for each specimen, including source, specimen ID, medical record number, turnaround time (TAT), workstation, sampling location, arrival timestamp, inspection items, and current processing status. This comprehensive data infrastructure supports both real-time operational management and retrospective performance analysis. For example, specimen No. 1410090173, originating from the outpatient department, was processed in LAB1 and completed with a

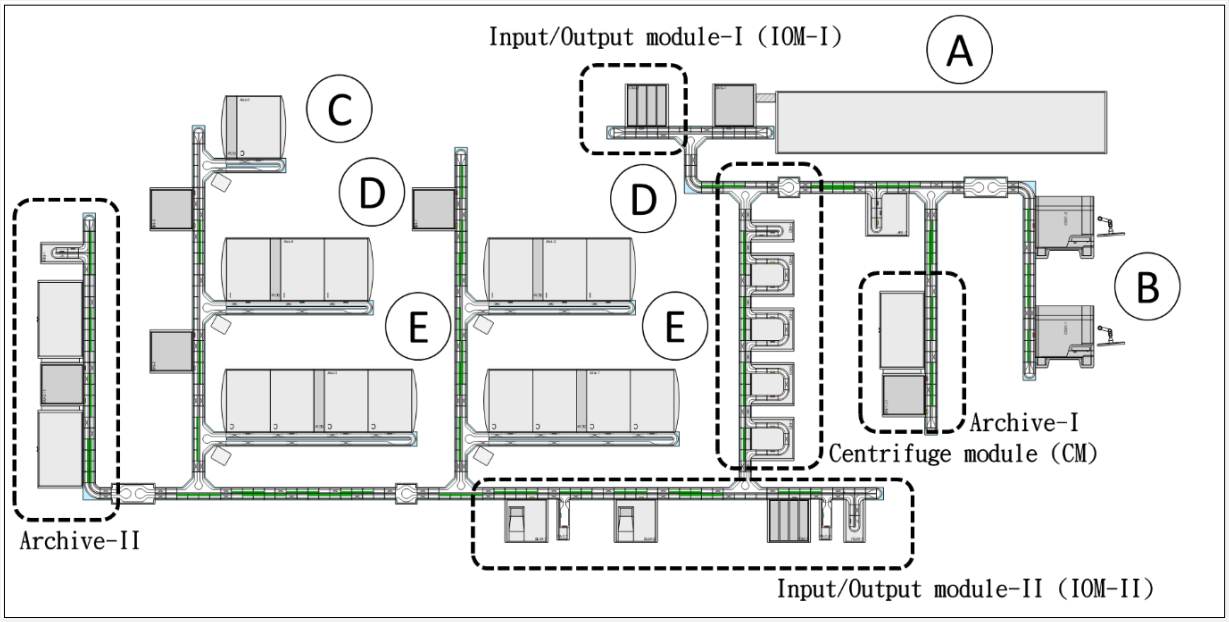
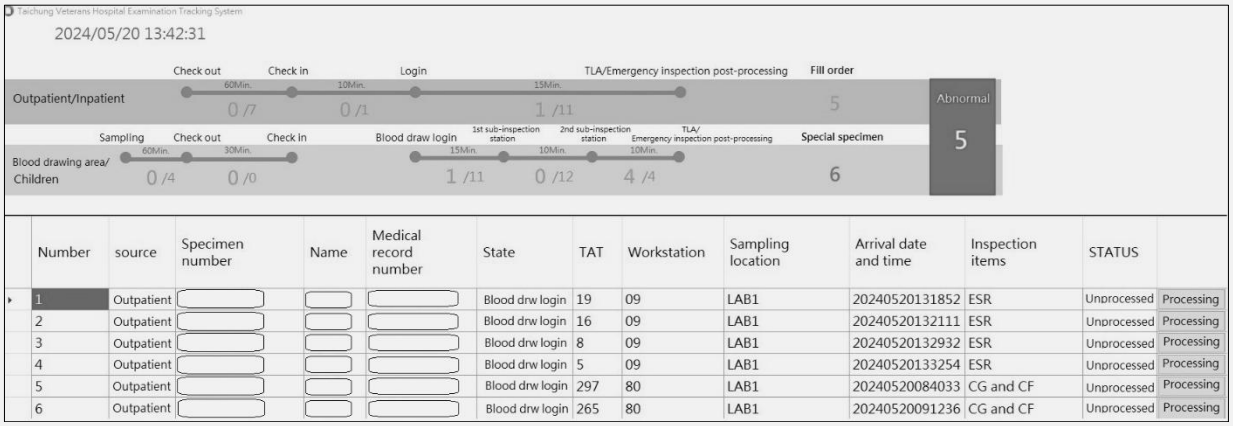


Figure 1. Map of the total laboratory automation (TLA) layout.

The circled English letters A to E represent different laboratory workstations, sequentially corresponding to the hematology, coagulation, HbA1c, serological immunology, and biochemistry workstations. The dashed-line boxes represent different functional modules of the TLA system.



	Number	source	Specimen number	Name	Medical record number	State	TAT	Workstation	Sampling location	Arrival date and time	Inspection items	STATUS	
▸	1	Outpatient				Blood drw login	19	09	LAB1	20240520131852	ESR	Unprocessed	Processing
	2	Outpatient				Blood drw login	16	09	LAB1	20240520132111	ESR	Unprocessed	Processing
	3	Outpatient				Blood drw login	8	09	LAB1	20240520132932	ESR	Unprocessed	Processing
	4	Outpatient				Blood drw login	5	09	LAB1	20240520133254	ESR	Unprocessed	Processing
	5	Outpatient				Blood drw login	297	80	LAB1	20240520084033	CG and CF	Unprocessed	Processing
	6	Outpatient				Blood drw login	265	80	LAB1	20240520091236	CG and CF	Unprocessed	Processing

Figure 2. Specimen tracking monitor system.

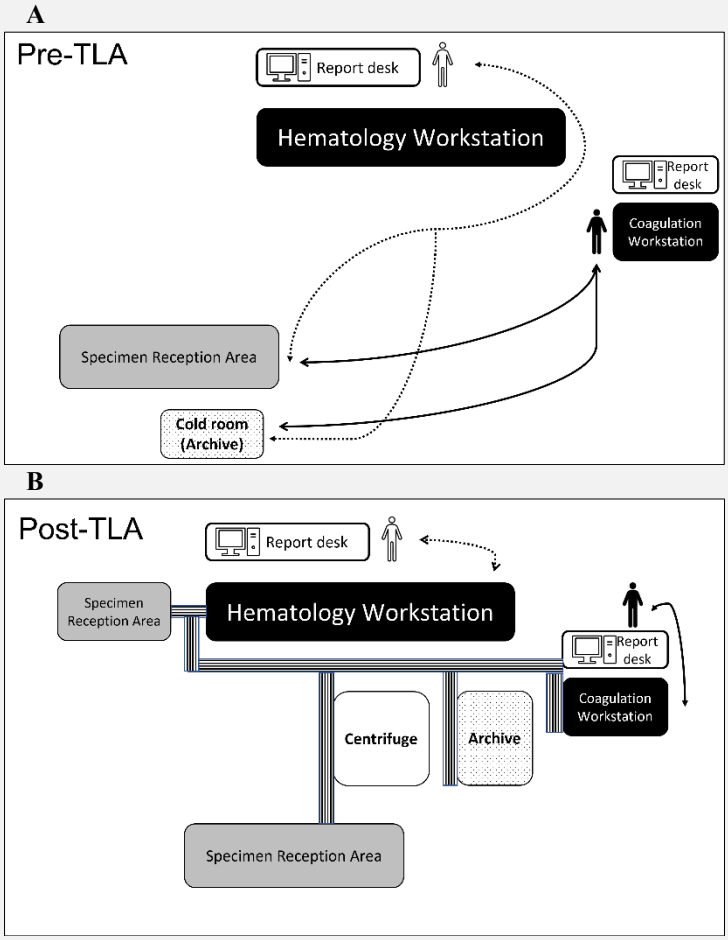


Figure 3. Changes in staff workflow before and after system implementation.

A: Pre-TLA, B: Post-TLA.

TAT of 19 minutes, demonstrating both system responsiveness and traceability. Overall, the implementation of this tracking system significantly reduced the incidence of misplaced or delayed specimens and improved laboratory efficiency in exception handling and workflow monitoring.

Staff workflow optimization before and after TLA implementation

To assess whether the implementation of total laboratory automation (TLA) could reduce staff workload and enhance operational efficiency, we compared the movement patterns of laboratory personnel before (pre-TLA) and after (post-TLA) system deployment, as illustrated in Figure 3. Prior to TLA implementation (Figure 3A), specimen processing involved multiple manual steps. Staff were required to frequently travel between the specimen reception area, hematology and coagulation workstations, the cold storage room (archive), and the report release desk. This workflow not only increased the risk of human error and processing delays but also placed a significant burden on staffing and resource allocation. Following TLA implementation (Figure 3B), specimen routing was automated via a central track system connecting the specimen reception area, centrifugation module, hematology and coagulation analyzers, and the archiving unit. This streamlined configuration substantially minimized unnecessary staff movement and manual specimen handling. Tasks that previously required human transport were taken over by the automated system, allowing laboratory personnel to shift their focus toward higher-value responsibilities such as data interpretation, quality control, and troubleshooting. Overall, the post-TLA setup not only enhanced workflow efficiency and specimen traceability but also contributed to a more ergonomic, less labor-intensive, and

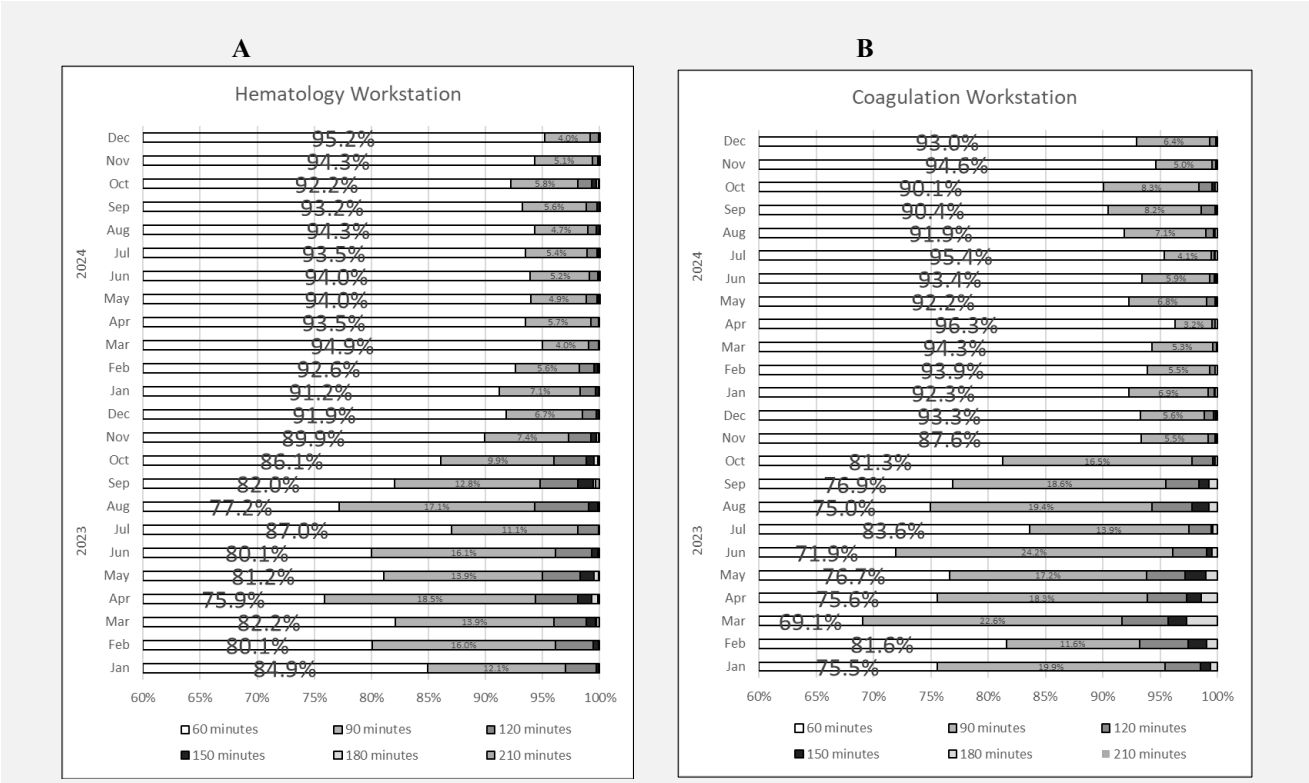


Figure 4. TAT improvement before and after TLA implementation.

Results are shown as achievable percentage of samples in each TAT criteria for A: Hematology Workstation, B: Coagulation Workstation.

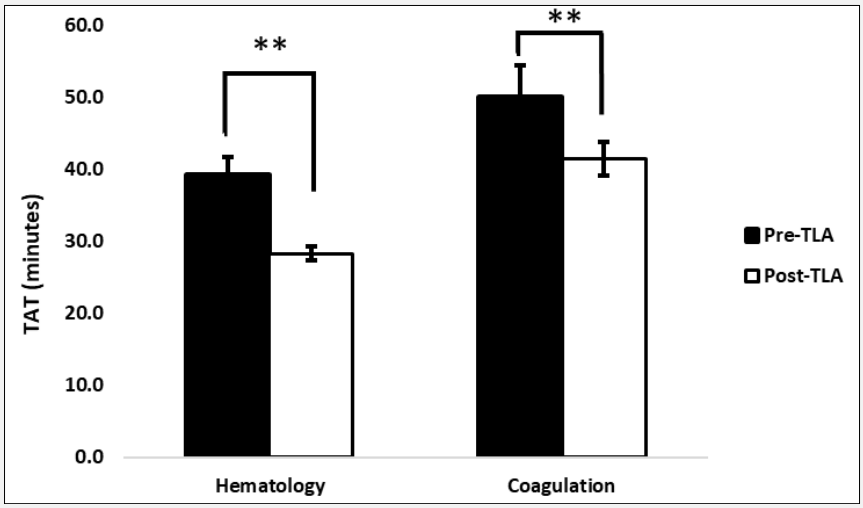


Figure 5. TAT improvement before and after TLA implementation.

The results are presented as the average sample reporting time during the pre-TLA period (April to September 2023) and the post-TLA period (April to December 2024). The mean TAT was significantly shortened from around 40 to 28 minutes in hematology and from nearly 50 to 38 minutes in coagulation, both improvements being stat ($p < 0.01$).**

safer working environment for laboratory staff.

Turnaround time (TAT) improvement following TLA implementation

To evaluate the impact of total laboratory automation (TLA) on operational efficiency, we compared the turnaround time (TAT) performance of hematology and coagulation workstations before and after TLA implementation. We observed monthly TAT distribution for hematology samples from January 2023 to December 2024 (Figure 4A). Prior to TLA implementation (highlighted up to September 2023), only 75 - 82% of samples met the 60-minute TAT target, with a substantial portion exceeding 90 minutes. Following implementation in October 2023, a steady improvement was observed. By April 2024, over 93% of hematology samples were consistently reported within 60 minutes, reaching 95.2% in December 2024. The proportion of delayed samples (> 90 minutes) also decreased significantly.

Similarly, Figure 4B shows the coagulation workstation results. Before automation, the 60-minute TAT achievement rate ranged from 69.1% to 83.6%, with up to 24% of samples delayed beyond 90 minutes. After TLA implementation, over 93% of samples consistently met the 60-minute benchmark, with delays dropping to below 7% by the end of 2024.

Figure 5 summarizes the overall improvement in average TAT for both workstations. The mean TAT for hematology decreased from approximately 40 minutes to 28 minutes, while for coagulation, it dropped from nearly 50 minutes to 38 minutes - both improvements being statistically significant ($p < 0.01$). These findings clearly demonstrate that TLA implementation significantly enhanced processing speed and efficiency, particularly by reducing delayed specimens and improving compliance with rapid-reporting standards essential for clinical decision-making.

Reduction in resource consumption and labor optimization

Following the implementation of total laboratory automation (TLA), the laboratory observed a notable reduction in consumable usage and manual labor requirements. Monthly consumption of blood collection tubes decreased by 2,915 tubes, leading to an estimated cost savings of USD 437 per month. This reduction was primarily attributed to more efficient specimen handling and test consolidation enabled by the TLA system, which minimized unnecessary duplicate collections. In addition to financial benefits, the environmental impact was also mitigated. The reduction in tube usage corresponded to a decrease of approximately 32 kilograms of CO_2 equivalent (CO_{2e}) emissions monthly, supporting the laboratory's efforts toward sustainable operations.

DISCUSSION

Implementation of TLA in our hematology and coagulation workstations yielded marked improvements in analytical performance and turnaround time (TAT). In our laboratory, the proportion of routine tests completed within one hour rose from ~ 82% to 95.2% for hematology and from ~ 83.6% to > 93% for coagulation after one year of full automation. This aligns with prior studies reporting significant TAT reductions with TLA. Several reports observed that connecting coagulation analyzers to an automated track system led to faster turnaround and higher throughput without loss of accuracy [12,13]. Similarly, other high-volume laboratories have documented > 13% decreases in median TAT following TLA adoption [14]. Such enhancements in speed and consistency have tangible clinical benefits, ensuring timelier result availability for critical decisions and improving overall diagnostic service reliability [14]. Notably, our combined hematology-coagulation automation system has demonstrated that even traditionally challenging specialties can achieve efficiency gains comparable to those seen in fully automated chemistry labs, which shows the broad impact of TLA on laboratory performance.

Beyond faster results, TLA fundamentally restructured our workflow and improved staffing efficiency. Automation eliminated nearly all manual specimen transport and routine handling steps, allowing us to reallocate or reduce personnel in those tasks. This experience mirrors findings in other institutions. A multi-site study by Al Naam et al. found that total automation significantly boosted productivity per technologist and allowed a higher test volume to be managed with a smaller workforce, a critical advantage for laboratories facing personnel shortages [15]. Importantly, rather than displacing skilled technologists, automation allows them to focus on higher-value tasks, e.g., investigating flagged abnormalities, performing manual smear reviews, and developing new assays, instead of repetitive chores [14, 16]. In our lab, technologists now devote more time to resolving complex or critical specimens. Overall, TLA has fostered a leaner workflow with fewer human touchpoints and error-prone steps, thereby improving efficiency while maintaining high-quality results.

Despite these clear benefits, implementing TLA in hematology and coagulation comes with challenges that require strategic planning and foresight. Integrating complex analyzers and processes involves significant upfront investment and infrastructure changes - automated track systems demand space and specialized facilities, and initial capital and maintenance costs can be high [11]. Lippi and Da Rin have noted practical hurdles such as increased equipment expenditure, workflow disruptions during transition, and even ancillary issues (e.g., added noise/heat and risk of downtime) that laboratories must anticipate [17]. Additionally, hematology and coagulation present unique technical complexities for automation. Certain tasks (e.g., blood smear ex-

amination or special coagulation tests) are not fully automatable and still require manual oversight, which historically led many labs to implement only partial automation in these sections. Close collaboration with vendors and iterative workflow customization have been essential in our case to ensure that sample integrity and specialized requirements (such as platelet-poor plasma preparation for coagulation) are met without compromising the automated stream. Change management is another critical aspect because transitioning to TLA demands extensive staff training and a cultural shift to trust automated processes. Strong leadership and project management are needed to navigate this transformation, as highlighted by Ellison et al. emphasis on robust change management and clear performance metrics in sustaining a successful automation rollout [14]. Looking ahead, ongoing technological advances promise to further enhance TLA's impact. Smarter middleware and AI-driven algorithms are being explored to extend autoverification and decision support, potentially pushing routine TAT toward an ambitious "one-hour or less" goal for nearly all specimens [14]. Some laboratories have even aimed to eliminate separate STAT testing by consistently achieving rapid turnaround on all samples through TLA and process optimization [14].

Future TLA implementations will likely integrate digital morphology and advanced image analysis for hematology, enabling automated slide reviews and reducing the need for manual differential counts. Moreover, as automation becomes more widespread under cost containment pressures, we expect greater interoperability between systems and broader adoption even in mid-sized labs [17]. In conclusion, while the initial hurdles are non-trivial, our experience and the growing body of evidence suggest that with careful planning, continuous optimization, and staff engagement, the benefits of TLA in hematology and coagulation can far outweigh the challenges. This positions laboratories to deliver faster, more reliable results at lower cost, ultimately enhancing patient care and operational excellence in the long term.

Declaration of Interest:

All of the authors declare there is no conflict of interests.

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