Editorial

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Reshaping laboratory medicine through technological advances

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Several technological innovations have profoundly transformed the field of laboratory medicine over the past decades, reshaping the processes of screening, diagnosis, and patient monitoring. Historically reliant on manual techniques and labor-intensive procedures, modern laboratories have increasingly integrated automation, digitalization and data-driven tools to deliver faster, more accurate, and increasingly personalized diagnostic information. These advancements extend beyond operational efficiency, redefining the role of laboratory medicine in clinical care and redesigning the contributions of laboratory specialists within multidisciplinary healthcare teams [1].

Forerunners in this transformation have been automation and robotics (Table 1). Automated analyzers can process thousands of samples daily with minimal human intervention, thereby enhancing the overall quality of the entire testing process, increasing throughput, and reducing turnaround time (TAT). Total laboratory automation (TLA) systems, which integrate pre-analytical, analytical and post-analytical workflows, enable continuous processing from sample receipt to result reporting, allowing laboratories to meet increasing demand despite limited staffing [2, 3].

Artificial intelligence (AI) and machine learning (ML) are further revolutionizing *in vitro* diagnostics by enabling the rapid processing of large datasets, supporting clinical decision-making and enhancing diagnostic accuracy [4] (Table 1). Predictive analytics are increasingly used to flag critical test results and detect instrument anomalies. Recent advancements in point-of-care testing (POCT) technologies are enhancing the safety and reliability of decentralized diagnostics, enabling laboratory-quality analyses to be performed directly at the patient's bedside or in their home [1,5]. These innovations support the emergence of a new organizational model in laboratory medicine, centered on the paradigm of "global-of-care testing" [1]. Collectively, such technological progress is steering the field toward a more efficient, data-driven, and patient-centered diagnostic ecosystem, fundamentally redefining laboratory workflows and their clinical impact [6].

In this issue of the *Journal*, we publish four significant contributions that advance laboratory medicine toward frontiers that, until recently, would have been considered the realm of science fiction. The first of such articles reports the results of a pilot evaluation comparing the clinical performance of a fully automated blood collection robot with manual venipuncture in adult volunteers [7]. Using a self-controlled crossover design, both specimen quality and laboratory test results were evaluated. The robotic system demonstrated improved precision in controlling blood volume and anticoagulant ratios, resulting in more stable blood specimens compared to those obtained through manual collection. Statistically significant differences were observed in certain coagulation and biochemical parameters, which would ideally reflect superior consistency in blood mixing. Pain perception was also reduced with robotic venipuncture. Nonetheless, robotic collection required longer collection times and initially faced acceptance challenges among users. Although robotic venipuncture appears to enhance procedural standardization and patient comfort, further optimization and rigorous validation, including assessment of the hemolysis index, which was not addressed in the current study, are needed before these robotic systems can be recommended for widespread clinical adoption. The second article is conceptually linked to the previous, as it evaluated the early implementation of an autonomous mobile courier robot within a clinical laboratory for transporting specimens from the central accessioning area to three designated laboratory sections [8]. Data from the initial deployment of the robot were compared with the corresponding period in the previous year, when samples were manually transported. The implementation of the autonomous courier significantly reduced the TAT by 18 %.

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Table 1: Useful definitions about technologies that are re-shaping the landscape of laboratory medicine.

Term	Definition
Computer	An electronic machine capable of receiving, transmitting, storing, and processing information, solving the most varied problems with extraordinary speed and reliability.
Artificial Intelligence (AI)	Computer systems capable of performing certain tasks that normally require the use of human intelligence.
Machine Learning	Subfield of artificial intelligence that involves the design and development of algorithms and models capable of identifying patterns that can be used to make predictions, classify information, or inform decisions, all without requiring explicit programming for each specific task.
Large Language Model (LLM)	An advanced artificial intelligence system designed to analyze, interpret, and generate human language.
Robot	Any machine (with various degrees of anthropomorphic form) capable of performing human tasks with various degrees of autonomy.
Automation	Integration of technologies, systems, and methodologies designed to perform tasks or processes autonomously, minimizing or eliminating the need for human intervention.

By converting batch-based transport into a near-continuous workflow, the system increased delivery frequency and minimized extreme delays across all time-of-day intervals, without impacting analytical workflow or sample preparation. This study could hence demonstrate that robotic courier systems may enhance laboratory logistics by improving efficiency, predictability and safety, while freeing staff for higher-value tasks. Nonetheless, additional long-term evaluations and expansion to several other laboratory sections would be needed to confirm sustained cost-effectiveness and scalability. Regulatory compliance and integration challenges, especially regarding elevator use, are also key considerations that should be considered before widespread implementation. The third paper investigated the feasibility and analytical reliability of drone-based transport of biological specimens compared with conventional road transport in a tertiary hospital setting [9]. The research followed a two-phase design, encompassing first a stability study with samples collected from healthy volunteers and transported by drone, road or kept stationary as controls, followed by a pilot study involving paired samples from primary care patients transported via drone and road. A comprehensive panel of biochemical, hematological, and urinary analytes was analyzed to assess variability attributable to drone transportation. The findings demonstrated minimal analytical differences between drone and road transport for the majority of analytes. In the stability phase, a limited number of parameters exceeded reference change values, with some deviations likely associated with mild hemolysis. Although five analytes showed statistically significant differences in the pilot study, none displayed a clinically relevant bias exceeding 2 %. Although hemolysis rates were marginally higher in drone-transported samples during the stability phase, they were comparable between transport modes in the pilot phase. It was hence concluded that transportation by drones maintained specimen integrity and analytical performance while offering logistical advantages, thus supporting the use of these devices as a reliable and sustainable alternative to conventional means for sample delivery.

The last article presents a comprehensive scoping review of AI and ML applications in thrombosis and hemostasis across clinical and laboratory domains from 2020 to 2025 [10]. A total of 107 original studies were analyzed from major databases, with a primary focus on advancements in diagnosis. Clinical applications, representing approximately 85 % of studies, predominantly involve predictive modeling for venous thromboembolism, pulmonary embolism, deep vein thrombosis, anticoagulant management, and risk stratification, using AI techniques such as neural networks, random forests, and gradient boosting. Laboratory-focused applications, although fewer in number, addressed automated quality control, clot detection, and assay interpretation, thereby supporting diagnostic decision-making. Common limitations included a reliance on retrospective, single-center datasets, limited external validation, interpretability challenges with complex ML models, and difficulties in integrating AI into routine clinical workflows. The review also highlighted a gap between thrombosis and hemostasis experts and AI specialists, as well as challenges related to regulatory frameworks, data fragmentation and manual annotation. Future directions emphasize the development of large multicenter datasets, model transparency and explainability, prospective validation, strengthened collaboration and education, and the establishment of clear regulatory pathways.

A vast array of technological advancements is deeply reshaping laboratory medicine, driving a transition toward automation, digitalization, and data-driven diagnostics. Innovations such as autonomous robotic blood collection and specimen transport systems demonstrate practical benefits, including improved specimen quality, reduced TAT and optimized workflow. Concurrently, AI applications hold the potential to significantly support both clinical risk stratification and laboratory assay interpretation. Although some challenges remain in optimizing these technologies, achieving user acceptance, ensuring regulatory compliance, and integrating seamlessly within healthcare systems, these important developments mark a new era of efficient, precise, and patient-centered laboratory medicine.

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