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The Role of Automation in Clinical Laboratories: Enhancing Diagnostic Accuracy and Streamlining Turnaround Times through Advanced Technological Solutions

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Abstract

Background: Automation in clinical laboratories has emerged as a vital component in enhancing the accuracy of diagnostic processes and reducing turnaround times. The increasing volume of biological samples necessitates efficient management systems to maintain quality and traceability.

Methods: This study reviews various automated systems and technologies currently utilized in surgical pathology laboratories. It examines barcode scanning, laboratory information management systems (LIMS), and robotic devices designed for specimen handling and processing. Specific instruments, such as the Tissue-Tek Xpress® × 120 and PathTracker™, are highlighted to illustrate advancements in specimen monitoring and workflow management.

Results: The implementation of automation has significantly reduced human error and improved processing efficiency. Automated systems facilitate precise tracking of specimens throughout their lifecycle, from reception to analysis, thereby ensuring high standards of quality control. The study reveals that automated tissue preparation and embedding systems enhance consistency, reduce processing times, and enable personnel to focus on critical tasks like quality assurance.

Conclusion: The integration of automation in clinical laboratories is reshaping the landscape of surgical pathology, leading to improved diagnostic accuracy and enhanced patient outcomes. As technology continues to evolve, it is essential for laboratories to adopt these innovations while addressing potential ethical and legal challenges. Future advancements in machine learning and artificial intelligence promise to further refine diagnostic processes, making them more efficient and reliable.

Keywords: Automation, Clinical Laboratories, Diagnostic Accuracy, Workflow Efficiency, Pathology

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1. Introduction

Over the last decades, initiatives to standardize surgical pathology laboratory procedures and minimize manual labor have intensified, with the objective of improving diagnostic precision and patient care results. The management of anatomic pathology specimens is crucial, since loss or improper storage may result in significant diagnostic, legal, and ethical consequences. Optimal storage conditions need regulated temperature and humidity for paraffin-embedded blocks, with safe and traceable methods for glass slides [1, 2]. The Superior Health Council of the Italian Ministry of Health has emphasized these problems in its recommendations [3].

It is essential to maintain a safe and regulated chain of custody for biological samples from collection to storage, guaranteeing quality, traceability, and appropriate preservation. Enhancing compliance and process efficiency need systems that automate and streamline labeling, archiving, and search procedures. Automation, defined as the use of machines to substitute or augment human labor in a process, is essential [4].

Standardization in tissue processing, analysis, and reporting is a primary emphasis in surgical pathology, guaranteeing accuracy and consistency of diagnostic results, along with clarity in diagnostic communication [5]. Emerging technologies, such as digital pathology systems and artificial intelligence methodologies, are being developed and used to improve diagnostic precision; nevertheless, acceptance has been slow owing to apprehensions over data privacy, expense, and compatibility [6, 7]. Molecular pathology yields data that must be accurate and need established analytical protocols prior to adoption [8]. In this context, quality assurance and control methods are essential, acting as supplements to guarantee the precision and dependability of outcomes [9-11].

The meticulous monitoring, storage, and preservation of specimens are essential, influencing diagnostic precision, patient treatment, and research outcomes. The advancement of surgical pathology and patient care is significantly dependent on the use of sophisticated technology and defined protocols. This study delineates the current advancements in pathology laboratory automation, with the objective of fostering innovative tools and methods to assist operators, organizations, and, crucially, patients.

2. Monitoring specimens

It is essential to develop automated solutions to facilitate the monitoring and management of specimen workflows owing to the increasing number of specimens received. Barcode scanning technology and laboratory information management software (LIMS) are used to monitor the location, status, and processing stage of each specimen [12, 13].

Laboratories may reduce the likelihood of human errors and expedite the turnaround time for diagnostic tests by automating the workflow process for specimens. Automated systems may produce barcode labels for use on specimen containers for tracking purposes and alert laboratory personnel upon receipt of a specimen. The specimen's placement and status in the LIMS may be modified by scanning the barcode at each step of processing. This allows laboratory personnel to monitor each specimen's status, identify any delays or issues necessitating intervention, and ascertain who performed specific actions with the specimen and at when time.

PathTracker™ is a laboratory system designed for bulk barcode scanning, using technology to capture, process, analyze, and record all barcodes within the field of view, with a claimed scanning duration of 30 seconds for a 150-cassette processing basket. Damaged or inadequately printed barcodes are identified, and PathTracker™ subsequently offers a suite of repair tools to rectify these barcodes either automatically or manually, so assuring uninterrupted operation.

FinderFLEX is a robotic apparatus designed for the manipulation and scanning of cytohistological specimens. Utilizing a multi-articulated mechanical arm, FinderFLEX can autonomously manage and insert slides, macrosection slides, biopsy cassettes, super mega cassettes, and vials onto designated racks with complete security. The operator must activate the gadget and log in to include any fresh samples for storage. FinderFLEX employs a state-of-the-art barcode scanner that swiftly reads barcodes, QR codes, and Data Matrix 2D codes, interfacing directly with the LIS to guarantee an organized and traceable sample management and handling procedure. FinderFLEX recognizes and handles samples straight from their standard racks and containers, significantly decreasing handling times, aided by the automated transmission of the gripper fingers. The gadget has user-friendly software and a touchscreen display, allowing the operator safe access during emergencies.

3. Preparation of tissue

The significance of uniformity in tissue processing in anatomic pathology is paramount. It guarantees consistency by minimizing disparities and verifying that any deviations are from the samples themselves. This standardized method streamlines quality control, facilitating the identification and correction of any issues, such as contamination [14]. Furthermore, it improves the accuracy of diagnostic tests by averting changes in tissue structure or composition that may affect later studies. Ultimately, it streamlines laboratory operations, improving efficiency and conserving resources.

Historically, pathologists and technicians dedicated extensive hours to the manual preparation of tissue samples for diagnostic purposes. The advancement of automated procedures and instruments has enabled speedy, accurate tissue fixation and processing with little human intervention.

The Tissue-Tek Xpress® × 120 tissue processor facilitates the continuous optimization of the histology workflow through vacuum infiltration, ensuring consistent results in a rapid timeframe, uniformly distributing cases, and reducing workloads, processing substantial tissue specimens in 2.5 hours.

The HistoCore PEGASUS Plus tissue processor enables the concurrent execution of multiple protocols on a single instrument, offering a fully integrated system capable of individually documenting each cassette, including cassette ID, quantity, color, basket ID, user ID, and reagent details. Automated tissue fixation and processing provide many advantages over manual processing. Initially, since all procedures are rigorously controlled by the computer, automation reduces the likelihood of errors and variability in tissue processing. This may provide more accurate and dependable diagnostic results, improving patient care and outcomes. The second advantage of automation is accelerated processing times, since the computer can control the timing of each step to optimize efficiency. Ultimately, automation liberates laboratory personnel to focus on critical responsibilities such as quality control.

4. Automation in tissue embedding processes

Embedding is a crucial phase in the histology technique; after tissue preparation, this meticulous operation is performed manually and requires appropriate knowledge and expertise. The proper orientation of the tissue inside the paraffin is crucial, since a poorly orientated specimen may provide an uninformative slice and may cause tissue loss during cutting, adversely affecting the patient. The technician meticulously embeds surgical specimens and biopsies individually, ensuring their proper positioning, a procedure that is often labor-intensive and time-consuming. To optimize the conditions for the cutting process, skilled personnel with proficient manual dexterity are required. Automated embedding systems provide many advantages over human embedding, including enhanced productivity, uniform processing, and reduced manual labor.

The Synergy system automates the embedding of tissues inside processing procedures, therefore obviating the need to manually reopen cassettes and reposition tissues. The Synergy technology system comprises a meticulously designed rack, specific molds, and pads. The sponges used for the pads provide the proper orientation of specimens and aid in microtome cutting via a singular tissue processing and embedding technique.

The Tissue-Tek AutoTEC® a120, with Tissue-Tek® Paraform® cassettes and Tissue-Tek® Paraform® Tissue Orientation Gels (Sakura Finetek, Tokyo, Japan), is a part of Sakura's SMART automation initiative aimed at automating manual tasks and ensuring a seamless workflow in the laboratory. These gels are designed to firmly retain and maintain the orientation of small tissue samples. The Tissue-Tek® Paraform® Sectionable Cassette System offers a comprehensive solution for automating cassette embedding, achieving a throughput of up to 120 cassettes per hour, contingent upon the proper orientation of tissue during grossing. This technique secures the specimen throughout processing and embedding, reducing tissue loss and obviating the need for specimen reorientation.

Automated embedding solutions seem to surpass hand embedding, particularly for productivity and consistency. Automated embedding enhances the precision and dependability of diagnostic testing by reducing the likelihood of human error and unpredictability. It is important to note that tissues may significantly differ in size, shape, and consistency, and not all may be appropriate for automated embedding. Certain fragile or irregularly shaped specimens may need hand implantation to guarantee appropriate alignment and preservation.

5. Automated microtome

Microtomes, essential to pathology laboratories since the eighteenth century, have significantly revolutionized tissue analysis by generating ultra-thin slices for meticulous evaluation of cellular structures and exploration of disease pathology. Notwithstanding its essential function, microtome operation continues to be a craft, requiring adept manipulation and meticulous calibrations. The significant issues of slice thickness variation and tissue distortion need creative methodologies and improved automation to guarantee consistent and repeatable outcomes. The automated microtome functions by sectioning the tissue sample into small layers using a motorized cutting blade. The instrument's control panel facilitates the production of tissue sections of varying thicknesses by modifying the section thickness. The instrument's automation ensures consistent tissue segment thickness, hence reducing the likelihood of errors and erroneous diagnostic results.

Dainippon Seiki has created the AS-410M automated microtome, which autonomously executes high-precision histological cuts in accordance with the predetermined specifications for each instance or tissue type. The specimen is next transferred to a slide, where it is deposited and elongated; thereafter, the slide is placed in a drying room for collection. The resulting slices are very homogenous and of superior quality. Furthermore, the apparatus may include roughing modules, cut quality assessment, slide printing, and integration with the Laboratory Information System (LIS) to provide comprehensive traceability of the samples. The estimated output is 250 blocks for a 7-hour work shift, with the capability to operate 24 hours a day.

The Sakura Tissue-Tek AutoSection® Automated Microtome provides one-touch trimming and adjustable sectioning, along with several incorporated safety features. It aligns the block with the blade edge, guaranteeing accurate XYZ placement. This technique ensures uniform block orientation, irrespective of previous trimming or sectioning on other microtomes, so preserving both tissue and technician resources.

Limitations in the use of such technology may stem from the difficulty in reliably cutting exceptionally hard or brittle materials; also, minimal biopsy procedures may still need human intervention and skill to prevent the loss of valuable tissue.

6. Automation in slide staining and coverslipping processes

The use of automated staining technologies has expedited the processing of large sample volumes, reduced human error, and improved the uniformity, speed, and reliability of staining methods. Hematoxylin and eosin (H&E)-stained slides are fundamental to morphological diagnosis, and their significance is paramount [15]. The whole process may be automated, enhancing repeatability, accuracy, and dependability; specifically, automated individual staining protocols are often superior to batch-stained slides in digital pathology [16]. An instance of a single slide staining apparatus is the Ventana HE 600.

Immunohistochemistry (IHC), using labeled antibodies, is an effective diagnostic technique in pathology that facilitates the detection of specific antigens in tissue sections. Automation has enhanced IHC staining efficiency by optimizing incubation durations, temperature ranges, and reagent concentrations—factors essential for accurate antigen–antibody interactions. The automated methods reduce background noise and non-specific staining, hence enhancing the signal-to-noise ratio and the overall quality of the stained slides. Various businesses have developed modern automated staining systems to address the diverse requirements of pathology laboratories. An example is the VENTANA BenchMark series of automated slide stainers, which offers comprehensive IHC and in situ hybridization (ISH) staining solutions.

The BOND-PRIME automated staining platform of Leica Biosystems (Wetzlar, Germany) is capable of accommodating various workflow requirements, including batch, continuous, single slide, or STAT instances, as well as combinations thereof for both IHC and ISH applications. The Tissue-Tek Genie® system by Sakura Finetek (Tokyo, Japan) is a fully automated, random access stainer for immunohistochemistry (IHC) and in situ hybridization (ISH), with separate staining stations that may process slides with various antibodies and probes concurrently and at any time.

The coverslipping process is a crucial step in the creation of a high-quality histology glass slide. The quality of coverslipping is crucial, since air bubbles, an excess or deficiency of mounting media, and dry mounted slides might compromise the diagnosis. There are three categories of coverslipping techniques: the traditional glass coverslip, the liquid approach, and the film method. The film method is the only automated technique and has shown to be the most rapid, exhibiting much fewer air bubbles and staining variations than the other two techniques [17], so establishing it as the optimal approach for producing glass slides for digital scanners.

7. Cooperative robots

In many instances, automating manual operations proves to be difficult. Devices, even ones produced by the same manufacturer, may exhibit inadequate coordination for material transmission. A routine laboratory activity is relocating sections across rack systems, such as transferring samples from a staining platform to a coverslipping apparatus [18]. The procedure may be protracted and might lead to material loss owing to the potential for components to fall or shatter.

There are significant opportunities to improve production flow and effectively integrate multiple phases, with the need for more process development. The growing use of robotic systems for material transport across processes results from collaborative robotics. Collaborative robots, known as "cobots," are equipped with sensors that enable safe contact between humans and robots without the need for protective boundaries. Flexible, camera-assisted grasping devices enhance the efficacy of these systems, enabling successful operation. The Tissue-Tek SmartConnect® by Sakura exemplifies a state-of-the-art innovation in laboratory automation, integrating human proficiency with efficient and dependable procedures. This collaborative robot is designed to operate harmoniously with laboratory personnel, aiding in many duties while enhancing precision and efficiency.

Upon loading the Tissue-Tek Xpress® × 120 via SmartConnect, automatic tissue processing commences. SmartConnect then transmits the magazines autonomously to the Tissue-Tek AutoTEC® a120 embedder. Ultimately, SmartConnect provides standardized, high-quality, embedded blocks suitable for microtomy. By using such a system, laboratories may enhance workflow, reduce human error, and increase overall efficiency. Furthermore, the integration of advanced technologies into these systems, including machine learning and artificial intelligence, might provide more exact and accurate sample treatment, hence improving overall results.

8. Digital and computational pathology

The essential fields of digital pathology and computational pathology in contemporary diagnostic medicine are transforming physicians' methods for analyzing, diagnosing, and treating illnesses [7]. Pathology glass slide scanners have transformed digital pathology by facilitating the transfer of histology samples on glass slides into high-resolution digital pictures. This has improved information accessibility, storage, and exchange, promoting worldwide cooperation among healthcare experts. These scanners have markedly enhanced in speed, resolution, and functionality throughout time.

Prominent items in the market include the NanoZoomer series, Aperio, IntelliSite, Pannoramic series, and Axioscan. Each device provides exceptional picture quality, processing speed, and capacity, addressing the varied requirements of diagnostic labs and research institutions. Pathologists may see, analyze, and share high-resolution digital pictures of histological and cytological specimens due to the digitization of glass slides using full slide imaging, known as "digital pathology." This technology enables pathologists to interact remotely, consult global experts, enhance diagnosis accuracy, and expedite patient treatment [19].

Computational pathology focuses on the development and application of machine learning algorithms and artificial intelligence (AI) for the evaluation of digital slides. This technology allows for the extraction of measurable data from digital slides, facilitating the identification of unique patterns and biomarkers, hence enhancing diagnostic accuracy and allowing personalized treatment. The advancement of whole slide imaging technology, increased processing capabilities, and the availability of extensive annotated datasets have all facilitated the expansion of digital and computational pathology. Investment and research in these domains have escalated because to the rising need for diagnostic solutions that are more effective, precise, and economically viable.

The identification of cancer is a primary application of digital and computational pathology. Machine learning algorithms have achieved remarkable success in the automated detection and classification of several tumor types, including breast, lung, and prostate cancer. These algorithms can analyze digital histopathology pictures to detect neoplastic cells, distinguish benign tumors from malignant ones, and identify the subtypes and grades of malignancies [20-23].

In this context, such technology may alleviate the burden for pathologists, diminish interobserver variability, and provide more reliable and accurate diagnoses via the automation of certain operations [24]. To identify possible advantageous applications of AI in pathology, Heinz et al. executed an anonymous online poll with 75 specialists in computational pathology from academia and industry sectors [25]. The poll findings indicated that the most potential future use is the direct prediction of treatment response using standard pathology slides. Digital pathology is now being rigorously explored within several applications of translational medicine to forecast treatment responses and identify individuals who are most likely to benefit from therapy.

In the field of immuno-oncology, identifying patients who might get the most benefit from immune checkpoint inhibitor therapy (ICI), such as PD-1/PD-L1 inhibition, remains a significant and unresolved challenge [26]. Significantly, in addition to PD-L1 expression on tumor and immune cells, the immunological contexture characterized by tumor-infiltrating lymphocytes (TILs) has shown considerable predictive capability [27].

Park et al. have created an AI-driven system for the detection and quantification of tumor-infiltrating lymphocytes (TILs) in the tumor microenvironment, which may delineate three immunological phenotypes: inflamed, immune-excluded, and immune-desert [28]. The authors established that patients with inflamed tumors exhibit a superior prognosis regarding overall survival (OS) and progression-free survival (PFS). Specifically, patients with inflamed neoplasms and elevated PD-L1 expression experience a notable enhancement in survival compared to those with high PD-L1 expression but non-inflamed tumors. These findings highlight that the use of image analysis enhances accuracy and efficiency by automatically quantifying many characteristics that cannot be discerned visually.

In addition to tumor pathology, computational pathology is being explored and utilized in essential yet frequently overlooked domains such as transplantation pathology, a specialized field that analyzes post-transplant graft biopsy outcomes for rejection or graft damage, as well as organ donor biopsy for organ allocation, alongside various areas of functional and non-neoplastic pathology [29-31].

Digital and computational pathology evidently provide effective techniques for organizing and understanding extensive information from many sources, including genomes, proteomics, and clinical data, in the era of big data. Machine learning algorithms facilitate integrated data analysis, enhancing the comprehension of illness etiology and enabling the identification of innovative opportunities for diagnosis, prognosis, and therapy. A significant barrier to the incorporation of digital pathology into clinical practice, as identified by administrators, is to its expense. Ho and colleagues developed a financial prediction for the introduction of digital pathology at a big healthcare institution to assess possible operational cost reductions [32]. The anticipated savings were predicated on two primary advantages of digital pathology: (1) possible enhancements in workflow efficiency and laboratory consolidation; and (2) mitigated treatment expenses resulting from decreased interpretative mistakes by general, non-subspecialist pathologists. The authors estimated that overall cost reductions over five years might amount to around

$18 million. This indicates that if the expenses associated with purchasing and implementing digital pathology remain below this threshold, the return on investment becomes appealing to hospital management.

Various integrated digital pathology systems are presently being deployed globally, demonstrating the viability of digital pathology workflows in both small and large pathology departments that serve extensive and diverse healthcare organizations with intricate patient demographic profiles; additionally, official guidelines have been issued [33-35]. The significance of digital pathology in the instruction of anatomic pathology is unequivocal, supported by an increasing array of resources such as digital pathology atlases. Fundamental competencies such as feature identification, differential diagnosis formulation, annotation, photography, description, and presentation are enhanced by the use of these materials. The use of these materials seems to be important in mitigating the hesitance to adopt digital technologies among certain learners [36]. Consistently incorporating these materials into unrecognized case discussions, instructional compilations, and tutorials may significantly enhance and expedite the learning experience [37].

Notwithstanding considerable progress and potential applications, digital and computational pathology continues to face some unresolved challenges. The sensitivity of medical data necessitates the sharing of images and information among specialists, hence raising concerns about privacy and security. Standardizing digital imaging techniques, data formats, and annotation methodologies is essential for ensuring consistency and interoperability across diverse systems and organizations. Machine learning algorithms must undergo rigorous validation and testing prior to integration into clinical procedures to ensure their reliability and clinical value; techniques to mitigate model accuracy degradation in the presence of artifacts must also be established [38].

The emerging generation of pathologists must possess robust and extensive training in anatomic pathology while also broadening their cultural knowledge to encompass fundamental principles of computational pathology and image analysis, thereby bridging the cultural divide between medicine, computer science, and data analytics. This does not imply that pathologists must become hybrid professionals; however, they will need to collaborate with computer scientists to comprehend and address the potential limitations of emerging technological methods and, crucially, to be the primary agents in this paradigm shift. Despite these challenges, the future of digital and computational pathology remains promising, as it will enhance diagnostic accuracy and provide patients with a more comprehensive understanding of disease processes via the integration of novel imaging modalities and machine learning algorithms [39].

9. Systematic synoptic documentation

The use of structured reporting in pathology is crucial as it promotes consistency and thoroughness in documenting essential cancer information. This standardization enhances the clarity and use of reports for direct patient care while ensuring that essential data is consistently collected for secondary objectives, including research, quality assurance, and public health management. The International Collaboration on Cancer Reporting (ICCR) has been instrumental in advancing worldwide uniformity, therefore improving patient outcomes and facilitating advancements in cancer research [40, 41].

The ICCR aims to enhance patient outcomes by implementing worldwide standardized pathology reporting. The creation of evidence-based databases, including all pertinent and up-to-date reporting information for each particular disease, leads to more comprehensive pathology cancer reports, enhanced cancer staging, and the optimization of treatment regimens for cancer patients. In addition to dataset creation, the ICCR has identified two more critical areas of emphasis for the future. The first step involves translating datasets into various languages to facilitate the implementation of reporting standards in both developed and low-to-middle-income countries (LMICs). The second involves transforming dataset standards into machine-readable forms to enable electronic implementation and enhance worldwide data interoperability.

The development of evidence-based databases, including all critical and current reporting information for each individual malignancy, enhances the comprehensiveness of pathology reports and refines cancer staging and treatment strategies for patients. Moreover, these databases provide the foundation for establishing national networks among pathology labs, exemplified by the Pathological Anatomy National Automated Archive (PALGA), which has been operational in the Netherlands since 1971. The objective of this organization is to facilitate communication and information sharing among participating labs and to provide potentially beneficial data for healthcare practitioners in the interest of patient care and research [43,44].

10. Conclusions

Automation in surgical pathology has shown significant promise to improve accuracy, efficiency, and the overall quality of patient care. The use of new technology, including robots, artificial intelligence, and machine learning, enables pathology labs to minimize human error, optimize processes, and accelerate the diagnosis process. As these advances progress, it is imperative for the medical community to adopt and adjust to these developments while addressing any ethical and legal issues that may emerge. The future of surgical pathology is inextricably linked to improvements in automation, enabling more precise diagnosis, enhanced patient outcomes, and a deeper comprehension of illnesses.

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دور الأتمتة في المختبرات السريرية: تعزيز دقة التشخيص وتسريع أوقات الإنجاز من خلال الحلول التكنولوجية المتقدمة

الملخص

الخلفية :أصبحت الأتمتة في المختبرات السريرية عنصرًا حيويًا لتعزيز دقة عمليات التشخيص وتقليل أوقات الإنجاز. يزداد حجم العينات البيولوجية باستمرار، مما يستلزم وجود أنظمة إدارة فعالة للحفاظ على الجودة وإمكانية التتبع.

المنهجيات :تراجع هذه الدراسة الأنظمة والتقنيات المؤتمتة المستخدمة حاليًا في مختبرات علم الأمراض الجراحي. تشمل هذه الأنظمة ماسحات الباركود، وأنظمة إدارة معلومات المختبرات(LIMS) ، والأجهزة الروبوتية المصممة للتعامل مع العينات ومعالجتها. يتم تسليط الضوء على أدوات محددة مثل Tissue-Tek Xpress® × 120 و PathTracker™لتوضيح التطورات في مراقبة العينات وإدارة سير العمل.

النتائج :أدى تطبيق الأتمتة إلى تقليل الأخطاء البشرية بشكل كبير وتحسين كفاءة المعالجة. تسهل الأنظمة المؤتمتة التتبع الدقيق للعينات خلال دورة حياتها، بدءًا من الاستلام وحتى التحليل، مما يضمن معايير عالية للتحكم في الجودة. تكشف الدراسة أن أنظمة إعداد الأنسجة المدمجة المؤتمتة تعزز من التناسق، وتقلل من أوقات المعالجة، وتمكن الكوادر من التركيز على المهام الحرجة مثل ضمان الجودة.

الخلاصة :يُعيد دمج الأتمتة في المختبرات السريرية تشكيل مجال علم الأمراض الجراحي، مما يؤدي إلى تحسين دقة التشخيص وتعزيز نتائج المرضى. ومع استمرار تطور التكنولوجيا، من الضروري أن تتبنى المختبرات هذه الابتكارات مع معالجة التحديات الأخلاقية والقانونية المحتملة. تعد التطورات المستقبلية في التعلم الآلي والذكاء الاصطناعي بتطوير عمليات التشخيص وجعلها أكثر كفاءة وموثوقية.

الكلمات المفتاحية :الأتمتة، المختبرات السريرية، دقة التشخيص، كفاءة سير العمل، علم الأمراض.