AUTOMATION OF LABORATORY TESTING: ADVANTAGES AND LIMITATIONS

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Modern medical development is impossible without a highly effective laboratory diagnostics system, which plays a key role in the prevention, early detection, and monitoring of diseases. According to the World Health Organization, laboratory test results are used in up to 70–80% of clinical decisions, which underscores their exceptional importance in the healthcare system [1, 2]. With the rise in disease incidence, increased life expectancy, and more complex clinical protocols, the workload on clinical diagnostic laboratories is growing significantly. In recent decades, there has been a steady increase in the volume of laboratory tests, an expansion in the range of parameters measured, and higher requirements for accuracy, reproducibility, and speed of results [3]. Traditional, predominantly manual methods of performing laboratory analyses are in some cases unable to fully meet the modern needs of clinical practice, due to the high probability of pre-analytical and analytical errors, the dependence of results on human factors, and limited scalability [4, 5].

In this regard, the automation of laboratory research is considered one of the priority areas for the development of laboratory medicine. The introduction of automated analytical systems, robotic complexes, and laboratory information systems is aimed at optimizing work processes, standardizing research methods, and increasing the overall efficiency of laboratory activities [6, 7]. Automation minimizes the influence of subjective factors, ensures strict quality control at all stages of laboratory analysis, and reduces the time required to perform tests, which is especially important in emergency and intensive care settings [8]. Automation plays a special role in the pre-analytical stage, which, according to numerous studies, is the source of up to 60–70% of all laboratory errors [9]. The use of automated systems for sorting, centrifuging, dosing, and identifying samples contributes to a significant reduction in the frequency of errors associated with incorrect labeling, contamination, and violation of biomaterial storage conditions [10].

However, despite the obvious advantages, the introduction of automated laboratory technologies is accompanied by a number of problems and limitations. These include the high cost of equipment and software, the need to upgrade laboratory infrastructure, the complexity of integrating devices from different manufacturers, and the need for highly qualified personnel capable of working with modern automated systems [11–13]. In conditions of limited financial resources, these factors can significantly slow down the automation process, especially in small and medium-sized laboratories [14].

An additional challenge is the need to ensure information security and the protection of personal medical data when using laboratory information systems and digital platforms [15]. In addition, excessive technologization of the laboratory process without proper clinical control can lead to a decrease in the critical evaluation of research results and a formal approach to data interpretation [16]. In view of the above, a comprehensive analysis of the advantages and limitations of laboratory automation is a pressing scientific and practical task. Studying modern automated technologies, evaluating their effectiveness, and identifying problematic aspects of their implementation are important for the further improvement of laboratory diagnostics and the quality of medical care for the population [17–19].

Laboratory automation is the process of introducing technical, software, and organizational tools aimed at partially or completely replacing manual labor in the performance of laboratory analyses [1]. The goal of automation is to increase the accuracy, reproducibility, and speed of laboratory tests, as well as to optimize the use of human and material resources [2]. In modern medicine, automation is seen not only as a technological innovation, but also as a strategic tool for improving the quality of laboratory diagnostics and the clinical effectiveness of medical care [3].

From a scientific point of view, the automation of laboratory research can be defined as a systematic approach to laboratory process management, covering all stages of analysis — from the moment biological material is received to the issuance and interpretation of results [4]. This approach is based on the use of automated analytical instruments, robotic modules, laboratory information systems, and quality control tools [5]. Unlike traditional methods, automated technologies ensure standardization of procedures, reduce variability in results, and minimize the influence of the human factor [6]. The laboratory process is conventionally divided into three main stages: pre-analytical, analytical, and post-analytical [7]. Automation can affect each of these stages to varying degrees, which allows us to distinguish several levels of automation of laboratory research [8].

The pre-analytical stage includes the collection, identification, transportation, preparation, and storage of biological material [9]. According to numerous studies, it is at this stage that the greatest number of laboratory errors occur, related to incorrect sample labeling, violation of storage conditions, non-compliance with time intervals, and contamination of material [10]. Automation of the pre-analytical stage involves the use of barcoding systems, automatic sample sorting and distribution stations, robotic centrifuges, and devices for dosing and aliquoting samples [11]. The use of these technologies can significantly reduce the frequency of errors, improve sample traceability, and ensure strict quality control in the early stages of laboratory analysis [12]. In addition, automation of the pre-analytical stage helps to reduce material preparation time and increase the overall throughput of the laboratory [13].

The analytical stage is the central link in laboratory research and involves the direct performance of analyses using biochemical, hematological, immunological, and molecular genetic methods [14]. This stage is automated through the introduction of automatic and semi-automatic analyzers capable of performing a large volume of tests with high accuracy and reproducibility [15]. Modern automated analyzers enable the simultaneous performance of multiple tests, automatic calibration and internal quality control, as well as the recording and transfer of results to laboratory information systems [16]. This significantly reduces the operator's influence on the analytical process, minimizes the likelihood of technical errors, and increases the reliability of the data obtained [17]. The analytical level of automation is especially important in conditions of high workload and the need to perform urgent studies [18].

The post-analytical stage includes the processing, storage, transfer, and interpretation of laboratory test results [19]. Automation at this level is mainly carried out using laboratory information systems (LIS), which provide electronic document management, report generation, and integration with medical information systems [20]. The use of LIS speeds up the transfer of results to the attending physician, reduces the risk of information loss, and ensures the availability of data for subsequent analysis and monitoring of the patient's condition [21]. In addition, automation of the post-analytical stage contributes to the introduction of elements of clinical decision support, which increases the clinical significance of laboratory tests [22].

The automation of laboratory testing is one of the key areas of modernization in contemporary clinical diagnostic laboratories and is considered a crucial factor in improving the quality, efficiency, and safety of laboratory diagnostics [1]. With the growing volume of laboratory tests, increasingly complex diagnostic algorithms, and higher requirements for the accuracy of results, the introduction of automated technologies is becoming strategically important for the healthcare system [2].

One of the most significant advantages of laboratory automation is the improvement of analytical accuracy and reproducibility of results [3]. Automated analyzers operate on the basis of standardized protocols, which minimizes variability associated with subjective operator actions [4]. Eliminating manual steps such as dosing, mixing, and recording results significantly reduces the likelihood of technical and methodological errors, which is especially important when conducting highly sensitive biochemical, immunological, and molecular genetic studies [5].

An equally important advantage of automation is the reduction of human error at all stages of the laboratory process [6]. Manual labor is traditionally associated with the risk of errors caused by staff fatigue, high workload, insufficient qualifications, or violations of standard operating procedures [7]. The introduction of automated systems significantly reduces the likelihood of such errors, increases the reliability of the data obtained, and ensures the stable quality of laboratory services [8].

The automation of laboratory testing contributes to a significant increase in the productivity and throughput of laboratories [9]. Modern automatic analyzers are capable of performing hundreds and thousands of tests per day without compromising the quality of the results, which is particularly relevant for large diagnostic centers and multidisciplinary hospitals [10]. Reducing the time required to perform analyses speeds up the diagnostic process and improves the efficiency of clinical decision-making [11].

An important advantage of automation is the optimization of human resources [12]. By reducing the volume of routine manual operations, laboratory staff are able to focus on quality control, interpretation of results, and scientific and analytical activities [13]. This contributes to the professional development of specialists and the rational distribution of labor resources within the laboratory [14]. Automation also plays a key role in improving biological and occupational safety [15]. The use of closed analytical systems and robotic modules reduces the risk of staff contact with potentially infected biological material, which is especially important when working with infectious disease pathogens and toxic reagents [16]. In addition, automated systems provide strict control over the storage conditions of samples and reagents, which further enhances the safety of the laboratory process [17].

A significant advantage of automation is the improvement of quality control in laboratory research [18]. Modern automated platforms are equipped with built-in systems for internal quality control, automatic calibration, and monitoring of analytical parameters [19]. This allows for the timely detection of deviations, prevents the receipt of unreliable results, and ensures compliance with international standards for laboratory diagnostics [20]. The automation of laboratory testing also contributes to more efficient information exchange and data integration [21]. The use of laboratory information systems ensures the automatic recording, storage, and transfer of results to electronic medical systems [22]. This reduces the risk of data loss, speeds up access to test results, and increases the clinical significance of laboratory information [23].

Finally, automation is an important foundation for the development of personalized medicine and high-tech diagnostic approaches [24]. The high accuracy, speed, and scalability of automated laboratory systems create conditions for the implementation of comprehensive diagnostic algorithms, biomarker monitoring, and the individualization of treatment strategies.

Laboratory information systems (LIMS) are an integral component of automated laboratories, providing data flow management, results storage, and integration with clinical information systems [8, 15]. The use of LIMS increases the transparency of laboratory processes and improves sample traceability at all stages of research [23]. Modern LIMS support automatic report generation, quality control, and analytical validation of results, which complies with international standards for laboratory diagnostics [17].

Despite its obvious advantages, the automation of laboratory testing comes with a number of limitations. The main limiting factor is the high cost of equipment, software, and maintenance [5, 21]. In addition, the implementation of automated systems requires significant investment in staff training and the reorganization of laboratory processes [12]. Additional complications are associated with the integration of equipment from different manufacturers and ensuring the cybersecurity of laboratory data [20]. In conditions of limited funding, automation may not be economically feasible for small laboratories [2, 22].

The choice of the level of automation for laboratory testing depends on the laboratory's profile, the volume of analyses performed, available resources, and clinical tasks. Partial automation can be an effective solution for laboratories with limited capabilities, while large diagnostic centers strive to implement integrated automated systems. Thus, laboratory automation is a multi-level process aimed at improving the efficiency, quality, and safety of laboratory diagnostics. The rational implementation of various levels of automation allows for the optimization of laboratory activities and ensures compliance with modern clinical medicine requirements.

The automation of laboratory testing is an important step in the development of modern laboratory diagnostics and healthcare in general. It improves the accuracy, speed, and reproducibility of tests, reduces the influence of human error, and helps optimize resources. At the same time, automation comes with a number of limitations, including high financial costs, technical difficulties, and staff qualification requirements. In this regard, the effective implementation of automated systems requires a comprehensive approach that includes economic assessment, organizational preparation, and training of specialists. Thus, the automation of laboratory testing is a promising area that contributes to improving the quality of medical care and the development of modern clinical diagnostics.

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