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The Role of Automation and Artificial Intelligence in Enhancing Laboratory Testing Quality and Efficiency in Low- and Middle-Income Countries: Review

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Abstract

Background: The integration of automation and artificial intelligence (AI) into laboratory medicine has the potential to enhance diagnostic quality and operational efficiency, particularly in low- and middle-income countries (LMICs). These regions face significant challenges in healthcare delivery, including limited resources, inadequate infrastructure, and high disease burdens.

Methods: This review synthesizes current literature on the applications of AI and automation in laboratory settings, focusing on their impact on testing accuracy, efficiency, and patient outcomes. A comprehensive analysis of case studies and empirical data was conducted to evaluate the effectiveness of AI-driven technologies in addressing the unique challenges faced by LMICs.

Results: The findings indicate that AI technologies significantly improve diagnostic precision by automating routine tasks, enabling rapid data analysis, and enhancing decision-making processes. Case studies reveal that AI applications, such as machine learning algorithms and robotic systems, have led to substantial reductions in diagnostic errors and turnaround times. Furthermore, the implementation of AI has improved patient management through predictive analytics, facilitating early disease detection and personalized treatment strategies.

Conclusion: The adoption of automation and AI in laboratory medicine presents a transformative opportunity for LMICs to overcome existing healthcare disparities. While challenges such as data scarcity, infrastructural limitations, and ethical concerns remain, strategic investments in AI ecosystems can foster

sustainable healthcare improvements. Future research should focus on developing contextually relevant AI frameworks to maximize the benefits of these technologies in resource-limited settings.

Keywords: Automation, Artificial Intelligence, Laboratory Medicine, Low- and Middle-Income Countries, Healthcare Efficiency

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1. Introduction

In laboratory medicine, artificial intelligence (AI) has emerged as a transformative technology capable of fundamentally altering several aspects of healthcare delivery. Artificial Intelligence (AI) denotes a computer system's capacity to learn, reason, and make decisions—functions traditionally requiring human intellect. This technology allows computers to replicate human cognitive abilities, including information comprehension, complicated reasoning, and conclusion formulation. Artificial intelligence is used in laboratory medicine to enhance precision and efficiency, optimize diagnostic procedures, and assist in clinical decision-making. The significance of AI advancements in laboratory medicine lies in its ability to analyze vast quantities of data, identify patterns, and provide valuable insights rapidly and precisely. Artificial intelligence may aid in the interpretation of laboratory test results, prediction of patient outcomes, and facilitation of early illness identification via the use of machine learning algorithms. This technology has the capacity to enhance patient outcomes, reduce diagnostic mistakes, and refine treatment strategies [1, 2].

Artificial intelligence is profoundly influencing medical imaging, transforming diagnoses and patient care. AI algorithms have the capacity to attain a high degree of accuracy in identifying diseases in radiological images such as X-rays, computed tomography scans, and magnetic resonance imaging scans. Consequently, disorders such as cancer may be identified at an earlier stage, facilitating swifter and more effective treatment. Pathologists may use AI to enhance the accuracy and efficacy of diagnoses by analyzing histology pictures. Predictive analytics is a significant use of AI in laboratory medicine [3]. AI algorithms may identify risk factors, predict disease development, and inform choices on personalized therapy by evaluating extensive datasets that include patient information, test findings, and clinical outcomes. This may augment patient care, refine treatment strategies, and facilitate the advancement of precision medical methodologies [4].

Artificial intelligence technology has the capacity to support healthcare systems in low- and middle-income countries (LMICs). The phrase “low- and middle-income countries” categorizes nations based on their developmental and economic status. The World Bank categorizes countries into several income categories, such as low-income, lower-middle-income, and upper-middle-income, based on their Gross National Income per capita. Numerous socioeconomic indicators, including income levels, poverty rates, the condition of the healthcare system, and access to resources and services, characterize LMICs. Low- and middle-income countries are crucial for the advancement of AI in laboratory medicine. These countries often have challenges in health care, including limited resources, inadequate infrastructure, and a significant illness load [5]. AI technology can address these issues and improve healthcare delivery in low- and middle-income countries (LMICs). AI may facilitate clinical decision-making in resource-limited settings, enhance the precision of disease detection, and streamline diagnostic procedures. Low- and middle-income countries (LMICs) may mitigate healthcare inequities, enhance patient outcomes, and surmount access limits by using AI algorithms. The need for accessible and affordable healthcare solutions is closely linked to the advancement of AI in laboratory medicine inside low- and middle-income countries (LMICs) [4, 6].

Besides improving illness monitoring and facilitating early identification and treatment, AI algorithms may also assist in the interpretation of laboratory test results. It is essential to recognize that surmounting several challenges is crucial for the effective incorporation of AI in laboratory medicine inside LMICs. The challenges include data scarcity, the need for contextually and regionally suitable algorithms, ethical concerns, capacity enhancement, and infrastructure advancement. Cooperation and cooperation are vital for information exchange, resource allocation, and capacity enhancement in the domain of AI in laboratory medicine among low- and middle-income countries (LMICs), high-income nations, international organizations, and research institutions [4, 6].

This study intends to examine the history, relevance, and consequences of AI breakthroughs in laboratory medicine, with an emphasis on low- and middle-income countries (LMICs). A comprehensive review will be undertaken to examine the history and importance of AI breakthroughs in laboratory medicine, specifically on their implications for low- and middle-income countries (LMICs). This study will provide possible ways to address difficulties and improve healthcare outcomes in resource-limited settings via the use of AI. Evaluating the present condition of laboratory medicine in LMICs and pinpointing common challenges will provide essential insights to policymakers, healthcare practitioners, and researchers, facilitating informed decision-making and the progression of knowledge in the discipline.

2. An Overview of Laboratory Medicine in Low-And-Middle-Income Countries

Laboratory medicine is crucial for the detection, surveillance, control, and treatment of illnesses. Nevertheless, low- and middle-income countries continue to encounter significant obstacles in obtaining quality-assured laboratory tests, resulting in delayed or erroneous diagnosis and ineffective treatments. The issues stem from many factors, including ineffective supply chain management, absence of governmental standards for laboratory testing, insufficient infrastructure, and limited laboratory supplies and equipment. In recent years, measures have been implemented to tackle these difficulties and enhance laboratory medicine in LMICs [7]. The Lancet Series on Pathology and Laboratory care (PALM) in LMICs offers thorough analyses of the problems and shortcomings of PALM services, including recommendations for improving laboratory care. The proposed remedies include enhancing infrastructure, guaranteeing access to essential laboratory supplies and equipment, fortifying the personnel via mentorship and training initiatives, implementing quality management systems, and creating governmental standards for laboratory testing. Furthermore, initiatives such as the Lancet Commission on Diagnostics emphasize the need of improving access to diagnostics, especially laboratory testing, in low- and middle-income countries (LMICs). The commission supports technological advancements and evidence-based essential diagnoses lists, emphasizing COVID-19, antibiotic resistance, and global health security [8-11]. Enhancing mentoring programs, investing in infrastructure development, extending educational and training opportunities, and implementing effective quality assurance systems are essential for strengthening laboratory medicine in LMICs. Cooperation among LMICs, high-income countries, international organizations, and research institutions is essential for information exchange, resource sharing, and capacity development [7,12].

The advancement of AI in laboratory medicine presents both opportunities and obstacles for LMICs. Access to comprehensive and high-quality data in LMICs may be hindered by inadequate infrastructure, insufficient digitization, and a disordered healthcare system [13]. There exists a deficiency of information, resources, and expertise necessary for the implementation of AI. Maintaining patient confidence and safeguarding sensitive data need the assurance of data privacy, security, and confidentiality, which may provide issues with ethical and legal concerns [14].

Notwithstanding these challenges, efforts are underway to eliminate the barriers to the integration of AI in laboratory medicine inside LMICs. Leveraging AI's potential requires investment in digital infrastructure, the creation of data-sharing networks, and the standardization of data. Moreover, innovative financial frameworks and public-private partnerships might render AI technology accessible and affordable in low- and middle-income countries (LMICs) [5].

Initially, the availability and cost-effectiveness of diagnostic technologies facilitate the timely and precise identification and monitoring of illnesses, which are crucial for health care management in LMICs. These breakthroughs facilitate early illness detection, consequently aiding in the cessation of disease development, minimizing complications, and enhancing patient outcomes [15]. Furthermore, by facilitating personalized and tailored therapies, these advancements enhance resource efficiency. Maximizing the efficiency of constrained healthcare resources is essential. Accessible and cheap diagnostic technologies in low- and middle-income countries enable healthcare professionals to make educated decisions, resulting in successful treatments, minimized unneeded interventions, and economical strategies [16].

Furthermore, these technologies facilitate the integration of machine learning models and artificial intelligence algorithms into laboratory medical practices. AI needs precise and comprehensive data for training and validation, which may be produced using readily available diagnostic tools. This combination facilitates the development of AI-driven diagnostic tools that improve accuracy, speed, and efficiency in diagnoses, including automated image processing systems and predictive models [17]. Prioritizing the development of accessible and cheap diagnostic tools is essential for maximizing the promise of AI in laboratory medicine within low- and middle-income countries (LMICs). This necessitates the allocation of resources for research and development focused on producing cost-effective solutions specifically designed for the unique requirements of LMICs. The implementation of these technologies may be rendered more economical, accessible, and sustainable via partnerships among governmental bodies, healthcare organizations, and technology providers [18].

3. The function of laboratory medicine in healthcare provision

In low- and middle-income countries, laboratory medicine is essential for healthcare delivery. Primarily, laboratory medicine provides essential diagnostic services that facilitate the early identification, diagnosis, and monitoring of illnesses. Accurate and prompt laboratory testing is crucial for guiding clinical decision-making, therapy selection, and patient care. These tests include a broad spectrum of subjects, including cellular pathology, microbiology, clinical chemistry, and hematology. The results of these tests provide medical professionals with insights on a patient's health condition and guide the optimal course of action.

Moreover, laboratory medicine is essential for the surveillance and management of diseases. The information it provides on disease prevalence, outbreaks, and trends allows public health officials to efficiently monitor and mitigate health hazards. Laboratory medicine aids in the detection and surveillance of infectious illnesses, hence facilitating the execution of preventative measures, including vaccination initiatives and infection control methods [19].

Furthermore, laboratory medicine underpins research investigations, clinical trials, and the development of novel diagnostic tools and technologies. Research conducted in low- and middle-income countries may address regional healthcare challenges and enhance global understanding in laboratory medicine. The significance of laboratory medicine in providing healthcare in low- and middle-income countries (LMICs) is crucial for mitigating illness effect, assuring precise diagnosis, and enhancing patient outcomes.

4. Progressions In Artificial Intelligence in Clinical Laboratory Medicine

Despite the high level of automation in modern clinical chemistry and hematology analyzers, only a limited number of total laboratory automation (TLA) systems have been developed. The Cobas®, an essential automated laboratory tool from Roche Diagnostics, is capable of independently processing, analyzing, and storing samples. This apparatus is capable of performing sample sorting, decapping, quality control, aliquoting, and recapping of in vitro diagnostic specimen tubes when used alongside one or more connection modules inside a track system. The Accelerator is a highly automated device intended for preanalytical processes, perhaps linked to a multi-instrument core laboratory system, recently launched by Abbott Diagnostics. The Accelerator is advantageous due to its "open" nature, which allows for interaction with other systems, hence promoting the unification of testing across several laboratory specializations. The Power Express Clinical Automation system, TCAutomationTM, Aptio® Automation, and VITROS® Automation Solutions provide more instances of commercially available TLA systems. Centralized techniques have shown improvements in analyzer performance and reductions in human error [20-24].

The integration of TLA into microbiology and the subsequent transformation in this discipline were facilitated by recent advancements in the digitization of culture plate images and the ability to electronically scan incubated plates [20,25]. Clinical labs now use two commercially available microbiological automation systems: WASPLab® and KiestraTM. Both systems provide varying degrees of automation, from exclusive front-end processing (automated plating) to TLA. Historically, the microbiology sector of clinical laboratories has required considerable physical exertion. To enhance productivity and mitigate the persistent national shortage of medical laboratory scientists, automated processes have garnered more attention in recent years. This shift in practice has created 25 opportunities for the integration of ML-based solutions into these new processes.

Enhanced automation is beneficial as it lowers expenses, allows technicians to engage in more specialized tasks (such as microscopy, plate interpretation, and antimicrobial susceptibility testing), boosts efficiency (as assessed by LEAN or other metrics), shortens turnaround time, enhances performance, and streamlines various manual and labor-intensive clinical microbiology procedures [20, 24, 26]. The domain of molecular diagnostics has seen a profound transformation due to the advent of high-throughput and high-multiplexity nucleic acid technologies. These strategies have been facilitated in part by developments in machine learning. Many next-generation sequencing (NGS) approaches assess millions of tiny clusters of labeled nucleic acids via thousands of images at their core. These approaches generate vast quantities of data, necessitating the implementation of effective big data management pipelines, since individuals are unable to evaluate such extensive datasets alone [27-29].

High-dimensional, structured data sets generated by contemporary NGS tests may provide significant diagnostic and prognostic insights. The magnitude and intricacy of these data sets make the processing of NGS data laborious and time-consuming. Consequently, many software solutions use machine learning to expedite multiple stages in the next-generation sequencing data processing pipeline. This technique, similar to other machine learning applications, may enhance human interpretations or provide new diagnostic opportunities. These technologies facilitate variation identification, curation, and clinical interpretation [30].

5. The Influence of AI Progress in Laboratory Medicine In Low-And-Middle-Income Countries

A common perception exists that laboratory test results substantially impact about 70% of choices concerning diagnosis, treatment, and patient discharge. The escalating workload, surging healthcare expenses, and the need for heightened accuracy require the ongoing improvement of laboratory operations [31-35]. The capacity to provide accurate, readily accessible, and contextualized information has gained significance in the healthcare and laboratory medicine fields due to the emergence of big data and artificial intelligence. The use of AI in laboratory medicine has the potential to provide substantial progress, especially for those living in LMICs. The domain of artificial intelligence in healthcare focuses on analyzing vast amounts of medical data produced by diagnostics, medical records, claims, clinical trials, and related sources. This assessment is performed using sophisticated algorithms and software intended to emulate human cognitive functions. For AI algorithms to operate efficiently, it is essential that the laboratory data used is both accurate and dependable [37].

Artificial intelligence has emerged as a very promising instrument in laboratory medicine, presenting several current and prospective uses. A significant use is predicting laboratory test results from clinical and demographic data, thereby facilitating improved efficiency and personalized patient treatment. Moreover, AI has shown considerable promise in improving laboratory productivity by optimizing test ordering processes and minimizing superfluous testing. This technique can preserve resources and reduce healthcare costs. The domain of laboratory processes is now seeing a substantial revolution driven by the incorporation of AI. This connection has resulted in the automation of several processes inside labs, including sample preparation, analysis, and reporting. This enhances accuracy and efficiency while allowing laboratory professionals to focus on more complex tasks. Recently, there has been an increasing tendency to use automated processes to improve productivity and mitigate the ongoing national scarcity of medical laboratory scientists. Artificial intelligence has the capability to improve the effective distribution of limited resources, including human capital, equipment, and supplies. This may be accomplished by offering decision assistance, quality assurance, and predictive maintenance [38].

A further interesting domain for AI use is in the exact interpretation of laboratory tests. This entails the amalgamation of genetic, proteomic, and metabolomic data to provide more comprehensive and individualized diagnostic insights. Furthermore, the impact of AI encompasses the improvement of laboratory medical information systems [39]. This is accomplished by enhancing data management, security, and interoperability, therefore facilitating the seamless integration and use of information. In the field of pathology, AI-driven algorithms have shown considerable potential in classifying central nervous system cancers by DNA methylation profiling. This has the potential to enhance diagnostic precision and refine treatment strategies. The domain of digital pathology has significant benefits with the use of AI for image analysis. This integration may provide significant support in diagnosis, prognosis, and therapy selection [40].

The use of big data analytics and natural language processing allows AI to track illness trends and occurrences, leading to more precise and timely disease detection. Artificial intelligence can scan extensive and varied data sets, including as electronic health records, genetic information, imaging data, and social media content, to discern patterns and biomarkers that may signify the presence or risk of illness [41]. AI has the capacity to facilitate the prompt detection of several illnesses, including sepsis, cancer, and Alzheimer's, via the analysis of physiological data or brain scans. AI has the capacity to collect and evaluate data from many sources, including news headlines, internet forums, government reports, and scientific publications. This allows AI to efficiently track disease trends and epidemics. The use of mathematical models and machine learning algorithms allows artificial intelligence to aid in forecasting the emergence and effects of viral illnesses like COVID-19 [36].

Expert systems, chatbots, and mobile apps may communicate with patients and healthcare practitioners, offering assistance and decision support for diagnosis and treatment. This advice is based on evidence-based recommendations or patient-specific information. Artificial intelligence may aid in diagnosing skin lesions, ocular disorders, and TB by using picture recognition and deep learning algorithms. Robotics and artificial intelligence have the capacity to profoundly transform the medical industry. These modifications might enhance patient care, resource distribution, and public health results within healthcare systems, particularly in laboratory medicine in these areas, which face several obstacles [42-44].

6. Obstacles In Deploying AI in Laboratory Medicine in Low-And-Middle-Income Countries

AI models may facilitate the development of optimal pharmaceuticals and preventative care, enhancing accuracy and efficiency in customized medicine. However, several obstacles impede the use of AI in laboratory medicine inside LMICs. These challenges may be thoroughly analyzed by considering infrastructure, resources, staff, data management, and cultural issues [45].

Low- and middle-income countries often have infrastructural limitations with the adoption of artificial intelligence in laboratory medicine. Examples of this include inadequate laboratory facilities, an inconsistent power supply, restricted internet access, and insufficient hardware and software resources. There is a deficiency of proficient individuals capable of effectively using AI techniques and technologies for diagnosis and analysis. The absence of essential infrastructure and resources hinders the deployment and sustainability of AI technology in laboratory medicine [7,10].

A further impediment is restricted access to high-quality data for AI training. AI models need substantial quantities of high-quality data for training. Nevertheless, owing to constrained resources, disjointed health information systems, absence of interoperable electronic health records, and insufficient data management procedures, LMICs often have challenges in obtaining comprehensive and varied data sets. Inadequate data for training AI systems may lead to suboptimal performance and limited generalizability. Concerns over data privacy and security, coupled with insufficient data governance regulations, may aggravate data management in LMICs [46].

The integration of AI in laboratory medicine is significantly influenced by ethical considerations and regulatory frameworks. The use of AI in laboratory medicine raises ethical and legal issues, including patient privacy, data protection, informed permission, and liability problems [4]. Due to the potential absence of robust policies and frameworks in LMICs to tackle these issues, ambiguity and potential risks may emerge. Robust ethical norms and regulatory frameworks specifically designed for AI in healthcare are necessary to tackle issues related to bias, transparency, accountability, and liability.

Contextual bias arises from the substantial development and deployment of AI in high-income nations, coupled with the fact that the data used to generate AI systems is closely linked to the context of usage; hence, implementing such systems in low- and middle-income countries may lead to contextual bias. Integrating AI technology with current laboratory information systems in low- and middle-income countries may provide challenges. Obsolete technology, interoperability challenges, and insufficient technical expertise hinder the smooth exchange and integration of data between AI systems and laboratory processes [4].

Restricted access to quality-assured laboratory diagnostics is an obstacle. Access to superior laboratory diagnostics is essential for illness detection, monitoring, and treatment. Numerous LMICs, however, have challenges stemming from insufficient key infrastructure, laboratory supplies, fundamental equipment, skilled personnel, and effective quality control systems. These limits affect the reliability and precision of laboratory results, which may influence patient treatment [2,9].

In LMICs, constrained resources, inadequate personnel, and capacity limitations result in a deficiency in both the quantity and quality of laboratory services. A shortage of qualified laboratory experts, including pathologists and technicians, may impede the use of AI systems. The cost of implementing and maintaining AI systems may be a significant challenge for LMICs with constrained financial resources. AI technologies can need substantial expenditures in infrastructure, software, and continuous upgrades. Enduring financial frameworks and economical solutions are essential to guarantee the long-term viability of AI integration in laboratory medicine. Pathology and laboratory medicine are often underappreciated in low- and middle-income countries (LMICs), leading to inadequate investment, limited resources, and a lack of awareness of their importance. The deficiency of funding and awareness obstructs the development and use of AI technology in laboratory medicine [47].

The deficiency of resources and expertise for executing AI is an additional obstacle. In low- and middle-income countries, there is often a scarcity of data scientists and AI professionals capable of developing, implementing, and overseeing AI systems. Furthermore, in resource-constrained contexts, the cost of implementing AI technology and assimilating it into existing laboratory operations might be excessive. The challenges of integrating AI are further intensified by budget limitations and conflicting healthcare priorities.

Resolving these difficulties would need a comprehensive plan. It involves enhancing laboratory infrastructure, refining data collection and management systems, instituting ethical and legal frameworks, advancing capacity-building and training initiatives, and increasing awareness of the significance of pathology and laboratory medicine among policymakers and stakeholders [4, 5, 7].

7. Conclusion

This review article examines the advancements of AI in low- and middle-income countries (LMICs). AI technologies are profoundly transforming LMICs across several industries, including healthcare and medicine. Low- and middle-income countries have adeptly used artificial intelligence to overcome resource and infrastructural constraints, therefore promoting sustainable development. Nonetheless, several hurdles persist in the progression of AI; yet, AI has the capacity to mitigate inequities and promote transformational social progress in LMICs by fostering multidisciplinary partnerships, information sharing, and strategic investments. This essay elucidates the need of creating AI ecosystems specifically designed for LMIC settings to promote a more equal and inclusive global technology landscape.

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دور الأتمتة والذكاء الاصطناعي في تحسين جودة وكفاءة الفحوصات المخبرية في البلدان منخفضة ومتوسطة الدخل: مراجعة

الملخص

الخلفية :يوفر دمج الأتمتة والذكاء الاصطناعي (AI) في الطب المخبري إمكانيات هائلة لتحسين جودة التشخيص والكفاءة التشغيلية، خاصة في البلدان منخفضة ومتوسطة الدخل .(LMICs) تواجه هذه المناطق تحديات كبيرة في تقديم الرعاية الصحية، بما في ذلك محدودية الموارد، والبنية التحتية غير الكافية، وعبء الأمراض المرتفع.

الطرق :تستعرض هذه المراجعة الأدبيات الحالية المتعلقة بتطبيقات الذكاء الاصطناعي والأتمتة في البيئات المخبرية، مع التركيز على تأثيرها على دقة الاختبارات، والكفاءة، ونتائج المرضى. أُجري تحليل شامل لدراسات الحالة والبيانات التجريبية لتقييم فعالية التقنيات المدفوعة بالذكاء الاصطناعي في معالجة التحديات الفريدة التي تواجهها البلدان منخفضة ومتوسطة الدخل.

النتائج :تشير النتائج إلى أن تقنيات الذكاء الاصطناعي تحسن بشكل كبير دقة التشخيص من خلال أتمتة المهام الروتينية، وتمكين تحليل البيانات بسرعة، وتعزيز عمليات اتخاذ القرار. كشفت دراسات الحالة أن تطبيقات الذكاء الاصطناعي، مثل خوارزميات التعلم الآلي والأنظمة الروبوتية،

أدت إلى تخفيض كبير في الأخطاء التشخيصية وأوقات التنفيذ. علاوة على ذلك، حسّن تطبيق الذكاء الاصطناعي إدارة المرضى من خلال التحليلات التنبؤية، مما يسهم في الكشف المبكر عن الأمراض وتطوير استراتيجيات علاجية مخصصة.

الاستنتاج :يشكل تبني الأتمتة والذكاء الاصطناعي في الطب المخبري فرصة تحولية للبلدان منخفضة ومتوسطة الدخل للتغلب على التفاوتات الحالية في الرعاية الصحية. ورغم التحديات المتمثلة في ندرة البيانات، والقيود البنية التحتية، والمخاوف الأخلاقية، فإن الاستثمارات الاستراتيجية في أنظمة الذكاء الاصطناعي يمكن أن تعزز التحسينات المستدامة في الرعاية الصحية. يجب أن تركز الأبحاث المستقبلية على تطوير أطر ذكاء اصطناعي مناسبة للسياقات المحلية لتحقيق أقصى استفادة من هذه التقنيات في البيئات محدودة الموارد.

الكلمات المفتاحية :الأتمتة، الذكاء الاصطناعي، الطب المخبري، البلدان منخفضة ومتوسطة الدخل، كفاءة الرعاية الصحية