GEORGE BROWN PRESS
JOURNALS, BOOKS & PROCEEDINGS

Journal of Medicine and Life Sciences

Article

Generative AI for Advances in Biomedicine

Yiran Sun [1,2,*]

[1] Department of Biomedical Engineering, City University of Hong Kong, Kowloon, Hong Kong SAR, China
[2] School of Data Science, Lingnan University, Tuen Mun, Hong Kong SAR, China
* Correspondence: Yiran Sun, Department of Biomedical Engineering, City University of Hong Kong, Kowloon, Hong Kong SAR, China; School of Data Science, Lingnan University, Tuen Mun, Hong Kong SAR, China

Abstract: The rapid advancement of Generative Artificial Intelligence (GenAI) has sparked widespread interest in the field of medical imaging, revealing unprecedented potential in diverse biomedical applications. Recent developments have enabled GenAI systems to perform at a level comparable to experienced clinicians, capable of generating highly accurate and structured medical reports, providing auxiliary diagnostic suggestions, and supporting complex clinical decision-making processes. By automating routine documentation, analyzing imaging data, and integrating multimodal patient information, GenAI can significantly reduce physician workload, minimize diagnostic errors, and improve the efficiency and clarity of doctor-patient communication. Beyond immediate clinical utility, these technologies hold promise for personalized medicine, predictive diagnostics, and large-scale epidemiological studies, offering transformative opportunities to enhance healthcare delivery and optimize clinical workflows. As research continues, the integration of GenAI into standard medical practice may redefine the role of clinicians, promoting more informed, data-driven, and patient-centered care.

Keywords*:* generative AI; medical imaging; structured medical reports; auxiliary diagnosis; clinical decision support

Received: 17 September 2025
Revised: 22 September 2025
Accepted: 07 October 2025
Published: 12 October 2025

1. Introduction

1.1. Generative AI Overview

Generative Artificial Intelligence (GenAI) has rapidly emerged as a transformative force within the broader field of artificial intelligence. Unlike traditional AI systems that primarily focus on data analysis and pattern recognition, GenAI possesses the ability to generate novel content-including text, images, audio, video, and computer code-by learning complex patterns from diverse input data. Central to its capability are advanced algorithms and multimodal models, which enable the system to produce coherent and contextually relevant outputs across different data types. A notable milestone in the evolution of GenAI was the introduction of OpenAI's ChatGPT in late 2022, which demonstrated the system's potential in natural language processing and spurred accelerated innovation across multiple domains, ranging from creative content generation to technical problem-solving.

1.2. Applications in Biomedicine

In biomedical and clinical contexts, GenAI exhibits remarkable potential in auxiliary diagnosis and healthcare decision support. Leveraging deep learning techniques, it can efficiently process complex medical imaging data, including X-rays, CT scans, and MRI scans. The system is capable of automatically detecting lesions, measuring their size, analyzing structural tissue changes, and monitoring disease progression, thereby facilitating early diagnosis and timely intervention. Beyond imaging, GenAI can assess disease types, evaluate severity, and generate personalized treatment recommendations, significantly enhancing diagnostic accuracy, reducing physician workload, and improving overall clinical workflow efficiency.

Furthermore, GenAI is increasingly applied in drug discovery and development. By integrating and analyzing vast datasets beyond human cognitive capacity, it can identify promising therapeutic compounds, optimize drug repurposing strategies, and provide data-driven insights that accelerate the drug development process. Collectively, these applications demonstrate how GenAI not only streamlines clinical operations but also advances precision medicine, predictive healthcare, and data-driven biomedical research, underscoring its transformative potential in modern healthcare.

2. Medical Imaging

2.1. Generative AI in Diagnostic Imaging

Generative Artificial Intelligence (GenAI) has become a transformative technology in medical imaging, fundamentally reshaping disease screening, diagnosis, risk assessment, and clinical decision-making. Leveraging advanced computational tools such as deep learning, Generative Adversarial Networks (GANs), and Transformer-based models, GenAI has been applied across multiple imaging domains, including neuroimaging, thoracic, abdominal, cardiac, musculoskeletal, and breast imaging. These systems have demonstrated significant improvements in lesion detection, image recognition, disease classification, and outcome prediction. Studies indicate that GenAI not only enhances diagnostic accuracy but also accelerates clinical workflows. For example, it supports rapid stroke classification, pulmonary nodule evaluation, early detection of liver cancer in cirrhotic patients, coronary plaque quantification, and automated assessment of musculoskeletal injuries. In breast cancer screening, GenAI has already demonstrated effectiveness in large populations and may eventually supplement-or partially replace-the traditional double-reading workflow. As these systems increasingly integrate multimodal data and expand into broader clinical applications, they are becoming key drivers of precision imaging and more efficient healthcare delivery.

2.2. GLLMs as Clinical and Educational Assistants

Generative Large Language Models (GLLMs) further enhance the impact of GenAI by providing real-time information retrieval, contextual reasoning, and interactive feedback. In medical imaging, GLLMs serve as both diagnostic support tools and educational platforms. They assist medical students and residents through self-paced or interactive learning, accelerating training and alleviating workforce shortages. Clinically, GLLMs aid in routine case management, support the diagnosis of common diseases, answer patient questions regarding risks and treatments, and improve overall workflow efficiency. For rare or region-specific conditions that are prone to misdiagnosis, GLLMs offer diagnostic reminders and supplementary insights. Beyond professional use, these models empower patients, families, and the general public to access reliable medical knowledge, thereby promoting health literacy and broad societal awareness of medical topics. GLLMs also demonstrate particular promise in ultrasound medicine, where they can generate structured reports, answer domain-specific medical questions, and assist in grading disease severity and management.

2.3. Limitations and Future Directions

Despite their transformative potential, GenAI and GLLMs have limitations compared with expert radiologists. Evaluations using over 150 multiple-choice questions without actual medical images show that these models perform well in basic recall and routine clinical decision-making but encounter challenges with higher-order tasks, such as describing imaging findings, performing quantitative calculations, classifying complex conditions, and applying visual data to clinical reasoning [1]. Currently, GenAI is predominantly applied in case management and the diagnosis of conditions such as breast and thyroid nodules, as well as liver dysfunction [2]. Future developments aim to improve model accuracy, multimodal data integration, interpretability, and clinical applicability. With continuous advancement, GLLMs are expected to achieve greater efficacy in ultrasound medicine, optimize diagnostic performance, expand the scope of applications, standardize clinical procedures, and enhance patient experience, ultimately contributing to safer, more efficient, and patient-centered healthcare.

3. Drug Development

3.1. Overview of AI in Drug Development

Artificial intelligence-driven drug development (AIDD) has emerged as a transformative approach in pharmaceuticals, encompassing multiple stages, including target identification, drug discovery, preclinical experiment design, clinical development, and drug repurposing. Among these, target and drug discovery, as well as clinical research, represent the primary areas with significant market potential and high research demand. With the rapid growth of computational power and data availability, traditional computer-aided drug design (CADD) has evolved into AI-driven drug development, enabling more efficient, accurate, and scalable processes. GenAI technologies have been widely adopted across drug development and regulatory frameworks, accelerating drug discovery, enhancing success rates, and fostering advances in regulatory science. Regulatory authorities globally have supported the integration of AI throughout the drug lifecycle through legislation, policy guidance, and the creation of collaborative technological ecosystems.

3.2. Target Discovery and Preclinical Research

The early stages of drug development rely heavily on identifying and validating promising biological targets. With AI-particularly deep learning and large language models-researchers can integrate diverse biological and biomedical data, including genomics, scientific literature, electronic health records, and real-world evidence, to detect patterns and relationships between genes, molecular mechanisms, and disease phenotypes [3,4]. This integration significantly accelerates the identification of potential drug targets. AI-powered platforms can also assist in rational drug design by predicting the interactions between small molecules and targets, enabling rapid development of novel compounds and early preclinical testing [5]. Such platforms streamline candidate selection, optimize molecular properties, and provide in silico validation before laboratory experiments, reducing time and cost while increasing the likelihood of therapeutic success.

3.3. Clinical Trials and Future Prospects

AI is increasingly transforming clinical trials by improving efficiency, patient recruitment, and monitoring. By analyzing both structured and unstructured data-including trial registries, literature, social media, and electronic health records-AI can match patients to appropriate studies more accurately and rapidly [6]. Large language models assist in identifying suitable participants, reducing screening time, while machine learning algorithms predict treatment responses, enabling more personalized and effective interventions [7,8]. Beyond recruitment, AI-powered tools such as wearable devices and digital adherence trackers facilitate remote monitoring, improve treatment compliance, and enhance data collection [9]. Interactive AI systems also streamline follow-up procedures, reduce participant burden, and improve the overall trial experience [10,11].

Looking forward, the convergence of AI, innovative management strategies, and integrated regulatory support is poised to unlock the full transformative potential of AI in drug development. This convergence promises to accelerate discovery, reshape development paradigms, and address an expanding spectrum of clinical needs with enhanced precision, efficiency, and patient-centered outcomes.

4. Neuroscience

4.1. AI in Neurological Disease Diagnosis and Management

Neurological disorders represent one of the leading causes of death and long-term disability worldwide, imposing substantial economic and emotional burdens on patients and their families. Many neurological conditions, such as neurofibromatosis (NF-1, NF-2), gliomas, auditory neuromas, and Alzheimer's disease, remain challenging to treat due to complex etiologies, heterogeneous clinical presentations, and limited standardized treatment protocols.

In recent years, the rapid advancement of artificial intelligence (AI) and the accumulation of extensive medical data have provided unprecedented opportunities to address these challenges. AI excels at handling large-scale, heterogeneous, and often noisy datasets, uncovering hidden patterns, and generating predictive insights that are beyond the capacity of human analysis. Machine learning models, in particular, can integrate diverse data types-including neuroimaging, genetic information, and electronic health records-to provide a comprehensive understanding of neurological conditions. These capabilities enable risk prediction, improved diagnostic accuracy, and personalized treatment planning, supporting precision medicine approaches in neurology [12]. As AI technologies mature, they are transitioning from isolated analytical tools to systems that support full-cycle neurological care, enhancing decision-making across diagnosis, monitoring, and therapeutic guidance.

4.2. AI-Enhanced Neurorehabilitation and Intervention

AI has also significantly advanced neurorehabilitation and interventional neurology. Brain-Computer Interface (BCI) systems, coupled with AI algorithms, have demonstrated the ability to decode neural signals and generate control instructions that directly stimulate spinal nerves, substantially improving motor function in patients with spinal cord injuries [13]. Such systems facilitate recovery of hand grasping and fine motor skills and are increasingly moving toward commercial clinical deployment. For instance, AI-driven BCI solutions for upper limb rehabilitation in chronic stroke patients have received regulatory approval, enabling broader clinical use.

Furthermore, AI has been applied in neurosurgical interventions, particularly in automated intraoperative target localization for Deep Brain Stimulation (DBS). Using microelectrode recordings (MER), AI algorithms can precisely identify target locations in real time, reducing surgical duration, minimizing reliance on specialized neurophysiological expertise, and alleviating patient burden. Deep neural networks and feature synthesis algorithms have further enhanced the accuracy of automated MER analysis, ensuring reliable and consistent electrode placement and maximizing therapeutic outcomes [14]. The integration of AI in neurological interventions thus represents a major step toward safer, more precise, and efficient neurorehabilitation and neurosurgical care.

5. Oral Science

5.1. Generative AI in Oral Drug Development

Generative Artificial Intelligence (GenAI) has demonstrated substantial potential in oral medicine by accelerating and optimizing drug discovery, development, and clinical applications. By generating novel candidate molecular structures, GenAI enables researchers to efficiently identify potential therapeutic compounds, predict their pharmacokinetic and pharmacodynamic properties, and optimize both efficacy and safety profiles. This capability not only shortens preclinical research timelines but also reduces the risk of late-stage drug attrition, thereby lowering overall R&D costs.

In addition, GenAI enhances diagnostic workflows through automated analysis and annotation of oral pathological images and radiographic data, including dental X-rays, cone-beam computed tomography (CBCT) scans, and histopathological slides. By detecting early-stage lesions, characterizing tissue abnormalities, and quantifying structural changes, GenAI supports timely clinical intervention and improves the accuracy of disease staging. These functions not only facilitate individualized treatment planning but also aid in monitoring therapeutic responses over time.

Moreover, the integration of GenAI in oral pharmacology extends to the design of personalized therapeutics, leveraging patient-specific genomic, microbiome, and metabolomic data to predict drug responses and tailor treatment regimens. Combined with predictive modeling of adverse effects and potential drug-drug interactions, GenAI contributes to safer, more effective oral therapies. Beyond drug development and diagnosis, these technologies have the potential to support clinical decision-making, optimize workflow efficiency, and promote precision medicine in dental care. Collectively, the application of GenAI in oral medicine promises to advance translational research, enhance therapeutic outcomes, and ultimately improve patient care quality.

5.2. AI-Assisted Research and Scientific Writing in Oral Medicine

Large Language Models (LLMs) have become indispensable tools in oral medical research, education, and academic writing. They assist researchers by rapidly reviewing and synthesizing extensive scientific literature, generating structured abstracts, extracting key concepts and keywords, categorizing topics, and facilitating efficient access to the latest advancements [15]. By automating these processes, LLMs significantly reduce the time and effort required for comprehensive literature reviews, allowing researchers to focus on hypothesis generation and experimental design.

Beyond literature synthesis, LLMs can automate the creation of figures, tables, flowcharts, and other visual representations of data, while also organizing manuscript structures, managing references, drafting titles, and producing preliminary drafts in multiple languages. These capabilities streamline the research and publication process, enhance clarity and consistency in scientific communication, and reduce potential errors in manuscript preparation.

Moreover, LLMs support higher-level analytical tasks by integrating findings from multiple studies, identifying gaps or uncertainties in current knowledge, and proposing novel hypotheses or research directions. They can simulate experimental scenarios, generate predictive models, perform data analysis and programming tasks, and forecast experimental outcomes, thereby facilitating efficient study design and large-scale data simulation. In educational settings, LLMs can also provide personalized learning resources, assist students and trainees in understanding complex concepts, and support interactive teaching of oral medicine principles.

The widespread adoption of generative AI and LLMs in oral science not only enhances research efficiency and academic productivity but also promotes interdisciplinary integration. By linking molecular pharmacology, clinical practice, imaging, and computational modeling, these tools enable a more rigorous, systematic, and accelerated advancement of knowledge in the field, ultimately contributing to improved clinical decision-making, innovation in therapeutic strategies, and the overall quality of oral healthcare.

6. Challenges

Although generative artificial intelligence (GenAI) offers extensive application potential in the medical domain, its continuous development and deployment are accompanied by a range of complex risks and challenges. Beyond conventional concerns related to intellectual property, liability, and cybersecurity, the medical use of GenAI faces several domain-specific issues that merit careful consideration.

First, privacy protection is of paramount importance in healthcare applications. Medical datasets often contain highly sensitive personal information, necessitating robust techniques such as anonymization, pseudonymization, obfuscation, or encryption to safeguard patient identities and confidential data during model training. Simultaneously, the formulation and enforcement of comprehensive privacy regulations are essential to ensure lawful collection, processing, and usage of medical data while maintaining patient trust and ethical compliance.

Second, security and data integrity pose critical challenges. High-quality training data are foundational for reliable AI performance, yet medical datasets may contain inaccuracies, inconsistencies, or harmful content. If unchecked, models could propagate, amplify, or misinterpret such information, leading to potentially severe clinical consequences. To mitigate these risks, collaboration with clinicians and domain experts is crucial for rigorous data validation, filtering, and oversight, preventing tampering, corruption, or unintended leakage of sensitive or erroneous information.

Third, limitations in comprehension and reliability remain inherent to GenAI systems. These models lack genuine understanding of language or other data forms, making them unable to independently verify the authenticity or plausibility of generated content. Additionally, variability in outputs for identical queries can compromise reliability and reproducibility, emphasizing the necessity for continuous human supervision to ensure stable and accurate performance.

Finally, bias and fairness issues require careful management. Training datasets must represent diverse populations across dimensions such as race, gender, age, and cultural background to minimize systemic biases. Furthermore, economic factors-such as pricing strategies for AI tools-may exacerbate disparities in regional accessibility, necessitating proactive measures to promote equitable deployment and ensure that the benefits of GenAI are widely distributed.

7. Conclusion

Generative Artificial Intelligence (GenAI) is rapidly transforming multiple critical domains within the medical field. In medical imaging, GenAI enhances diagnostic accuracy and efficiency through advanced techniques such as image enhancement, artifact removal, image reconstruction, and cross-modal image synthesis. It also provides robust technical support for telemedicine and automated diagnostic systems, facilitating faster and more reliable clinical decision-making.

In drug development, GenAI demonstrates remarkable capabilities, including the generation of potential active molecules based on target structures, optimization of pharmacological properties, prediction of toxicity and metabolic pathways, and facilitation of personalized drug design through the integration of genomic and multi-omics data. These innovations substantially shorten research and development cycles, reduce costs, and improve the likelihood of therapeutic success.

Within neuroscience, GenAI supports brain image synthesis, neural activity simulation, disease prediction, and brain-computer interface applications, contributing to a deeper understanding of cognitive mechanisms and enabling early intervention and personalized treatment strategies for neurological and mental disorders.

In dental and oral medicine, GenAI aids clinicians in generating preoperative images and drafting medical documentation while also enhancing research, education, patient communication, and public health literacy. Its application improves the efficiency, precision, and overall quality of healthcare services.

Overall, GenAI is progressively steering medicine from an experience-driven paradigm toward a data-driven model. Its value in enhancing diagnostic and therapeutic precision, accelerating scientific research, and optimizing patient experience underscores its potential as an indispensable intelligent assistant in future healthcare systems. However, alongside its rapid adoption, it is essential to address challenges related to data privacy, ethical standards, and technical security to ensure the sustainable, responsible, and equitable integration of GenAI into medical practice.

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