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AI-assisted Precision Diagnosis and Treatment of Liver Disease: Current Status and Future

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Abstract: Artificial intelligence (AI) technology is driving the rapid development of precision medicine, providing new tools and ideas for early diagnosis, risk prediction, and individualized treatment of liver diseases. This paper summarizes the latest research progress of AI in precision diagnosis and treatment of liver diseases, focusing on the major diseases such as hepatocellular carcinoma, non-alcoholic fatty liver disease and drug-induced liver injury. It first summarizes the current traditional methods of imaging, laboratory testing and pathology diagnosis and their limitations; and then focuses on the value of deep learning image analysis, machine learning models based on electronic medical records, and multi-omics data integration in improving diagnostic accuracy and evaluating disease progression. The article further analyzes the strengths and weaknesses of AI applications, including the lack of data standardization, insufficient model interpretability, limited cross-center generalization capabilities, and ethical and privacy challenges. Finally, it looks at future directions in terms of multimodal fusion, interpretable AI and individualized closed-loop management. The aim of this paper is to provide a systematic reference for research and clinical application of precision diagnosis and treatment of liver diseases.

Keywords: Artificial intelligence; Precision hepatology; Multi-omics; Deep learning; Liver disease diagnosis; Clinical translation

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1. Introduction

1.1. Global burden of liver disease and clinical challenges

Liver diseases represent a significant global public health burden, particularly characterized by hepatocellular carcinoma, nonalcoholic fatty liver disease, and drug-induced liver injury. Hepatocellular carcinoma is one of the most lethal types of liver disease, with the number of new cases and deaths globally measured in the hundreds of thousands each year, and the majority of patients are in the middle to late stages of the disease at the time of diagnosis, missing the window for optimal treatment such as radical surgery or radiofrequency ablation [1]. The prevalence of non-alcoholic fatty liver disease and non-alcoholic steatohepatitis has been increasing rapidly in recent years, with a global prevalence of 25–30% in the adult population, and some patients may progress to liver fibrosis, cirrhosis or even liver cancer [2]. As early stage is asymptomatic, clinical intervention often lags behind, and the lack of widely recognized drug treatment options makes management difficult. Although the incidence of drug-related liver injury is relatively low, about 5 cases per 100,000 people per year, it is characterized by sudden onset, complex course, and easy to be misdiagnosed, and the risk is significantly elevated in patients with advanced age and multidrug combinations [3].

Overall, liver diseases cause about 2 million deaths per year, accounting for about 4% of all global deaths [4]. From a clinical management perspective, these diseases face multiple challenges: first, early diagnosis is difficult; non-alcoholic fatty liver disease often has no obvious symptoms, early imaging manifestations of hepatocellular carcinoma are atypical, and drug liver injury lacks specific biomarkers; second, individualized risk assessment is insufficient, and there is a lack of uniform fibrosis stratification, identification of susceptible populations, and monitoring standards for high-risk populations; third, there are limited therapeutic options; patients with early stage of hepatocellular carcinoma can be offered surgery Third, limited treatment options: patients with early stage liver cancer can receive surgical or interventional treatment, but most of them miss the opportunity; non-alcoholic fatty liver disease currently lacks specific drugs; drug-induced liver injury mainly relies on drug cessation and supportive therapy; fourth, unequal distribution of resources, and there is a significant gap between low- and middle-income countries in terms of screening, early diagnosis, and treatment of liver disease, which further exacerbates the inequality of global health.

1.2. Demand for the application of the concept of precision medicine in liver diseases

With the increasing burden of liver disease, the traditional diagnosis and treatment strategy based on group average is difficult to meet the clinical needs, and the concept of precision medicine has emerged. Precision medicine emphasizes individualized diagnosis and treatment based on the patient's genome, epigenome, proteome, metabolome and other multidimensional information to improve the accuracy of disease prediction, intervention and treatment. In the management of liver diseases, individualized diagnosis and treatment are of great value. For example, the molecular heterogeneity of hepatocellular carcinoma patients is extremely high, and there are significant differences in gene mutations, signaling pathway activity, and tumor microenvironment among different patients, which directly affects surgical indications, chemotherapeutic drug selection, and the effect of targeted therapy [5]. For NAFLD/NASH, precision medicine can achieve early intervention and reduce the probability of disease progression to liver fibrosis or hepatocellular carcinoma through genetic susceptibility assessment (e.g., PNPLA3, TM6SF2 genes) and metabolic risk stratification. In addition, the occurrence of pharmacological liver injury is closely related to an individual's ability to metabolize drugs, and genotypic information such as CYP450 and HLA can help predict high-risk patients so as to formulate personalized medication regimens and reduce the incidence of adverse reactions [6]. The concept of precision medicine not only guides individualized diagnosis and treatment, but also enables early risk prediction, identifying high-risk groups and optimizing the frequency of monitoring and intervention strategies through the combination of multi-omics data and biomarkers. Targeted therapy is one of the core applications of precision medicine, and selecting the most effective drug or treatment regimen based on a patient's molecular characteristics can significantly improve efficacy and reduce unnecessary side effects. Therefore, introducing the concept of precision medicine into the management of liver diseases not only helps to improve clinical efficacy and patient survival, but also provides a solid data and theoretical foundation for subsequent AI technology-assisted diagnosis and treatment.

1.3. The rise of artificial intelligence in the medical field

In recent years, the rapid development of artificial intelligence in the field of medicine has brought about profound changes in the mode of disease diagnosis and treatment.AI technology is centered on Machine Learning (ML), Deep Learning (DL) and multimodal data fusion, and it realizes prediction, identification and decision support by analyzing large-scale medical data [7]. Machine learning can extract patterns from clinical electronic health records (EHRs), laboratory indicators and medical record texts to build disease risk prediction models, while deep learning excels in medical image analysis, which can automatically identify foci, segment tumor boundaries, and assess the degree of malignancy of foci in liver images [8]. Multimodal data fusion further integrates imaging, clinical features and histology data, realizing all-round information complementarity and providing solid data support for accurate diagnosis and treatment [9].

In the field of liver disease, AI shows significant application potential. On the one hand, AI can assist in the early diagnosis of liver cancer, analyzing CT, MRI or ultrasound images through deep convolutional neural networks to achieve automatic detection and staging assessment of lesions. On the other hand, AI combined with multi-omics data can predict the disease progression of NAFLD/NASH and DILI susceptibility, providing scientific basis for individualized intervention and medication. In addition, AI models can support clinical decision-making, such as drug selection, surgical risk assessment, and efficacy prediction, thus improving diagnosis and treatment accuracy and efficiency. With the development of Explainable AI and multi-center data sharing, the clinical translation of AI in the precision diagnosis and treatment of liver disease has a broad prospect, which can realize the early warning, personalized treatment and long-term management of the closed loop, and provide strong technical support for the landing of precision medicine.

1.4. Purpose of this paper

Based on the background of high incidence and complex clinical management of liver diseases, the purpose of this paper is to systematically review the latest research progress of AI in precision diagnosis and treatment of liver diseases. Firstly, this paper will summarize the current status of AI application in the diagnosis, risk prediction and individualized treatment of major liver diseases such as hepatocellular carcinoma, NAFLD/NASH and pharmacological liver injury; secondly, it will analyze the strengths and limitations of AI technology in clinical practice, including the improvement of diagnostic accuracy, the early warning capability, and the challenges of model interpretability, data standardization, and cross-center application; lastly, this paper will look forward to the future development direction of AI in the future development direction of precision diagnosis and treatment of liver disease, such as multimodal data fusion, interpretable AI, individualized diagnosis and treatment closure, and clinical translation potential, which will provide reference for subsequent research and practice. By systematically combing the existing research and clinical application experiences, this paper aims to provide theoretical foundation and technical support for the realization of precision medicine for liver diseases.

2. Current status of precision diagnosis and treatment of liver diseases

2.1. Clinical diagnosis and treatment methods

Clinical diagnosis and treatment of liver diseases mainly rely on three major means: imaging, laboratory testing and pathologic diagnosis. Imaging is an important tool for early detection and staging, including ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI) [1]. Ultrasonography is commonly used for initial screening of liver disease due to its convenient, non-invasive and low-cost operation, but has limited sensitivity in the early staging of small lesions or fatty liver. CT and MRI can provide higher resolution imaging information, of which MRI is especially advantageous in the characterization of liver lesions, assessment of liver fibrosis and staging of liver cancer. In recent years, functional imaging techniques, such as dynamic enhancement MRI and elastography, have shown potential for early diagnosis of liver diseases and evaluation of therapeutic efficacy.

Laboratory tests are important aids in the diagnosis and treatment of liver diseases, including serum liver function indicators (e.g., ALT, AST, ALP, γ-GT), serum markers (AFP, PIVKA-II) and metabolism-related indicators. Serum markers have some value in liver cancer screening, liver fibrosis stratification and disease monitoring, but the specificity and sensitivity are still insufficient and easily interfered by inflammation, drugs or other diseases. Pathologic diagnosis, as the gold standard, mainly relies on liver puncture biopsy, which can clarify the pathological staging, degree of inflammation and fibrosis, and has irreplaceable value in the diagnosis of hepatocellular carcinoma and NASH. However, biopsy has invasiveness, sampling bias and risk of complications, which limits its wide application.

In terms of treatment, liver disease management relies on a comprehensive approach. Radical treatments for hepatocellular carcinoma include surgical resection, radiofrequency ablation, transarterial chemoembolization (TACE), and targeted drug therapies. The treatment of NAFLD/NASH relies on lifestyle interventions, such as weight loss, dietary modification, and exercise, with attempts at pharmacological treatments to ameliorate hepatic fat deposition and inflammation. The management of DILI is based on discontinuation of medications and symptomatic support, with a lack of targeted pharmacological interventions. Although the existing methods have improved the prognosis of patients to some extent, the low rate of early detection, insufficient individualized treatment and difficulty in predicting efficacy remain major limitations.

In summary, traditional imaging, laboratory testing and pathology diagnosis play an important role in the management of liver disease, but all suffer from insufficient early sensitivity, limited diagnostic specificity and insufficient individualization of treatment. These limitations provide a clear demand background for the application of precision medicine and artificial intelligence technologies in the diagnosis and treatment of liver diseases.

2.2. Application of precision medicine

As the complexity and individual differences of liver diseases continue to emerge, precision medicine has shown significant value in the management of liver diseases. By integrating multi-omics information, including genomics, proteomics and metabolomics, precision medicine can deeply analyze the molecular mechanism of liver disease development, and provide scientific basis for individualized diagnosis and treatment. For example, genomic analysis can identify mutated genes and signaling pathways related to liver cancer, which can help determine tumor typing and indications for targeted therapy; while proteomic and metabolomic data can reveal biomarkers of early stage of the disease, which can provide support for risk prediction and efficacy monitoring.

In terms of individualized risk assessment, precision medicine is able to combine clinical features and histological data to stratify patients' risk of disease development. For example, in NAFLD/NASH, analysis of the genetic markers PNPLA3 and TM6SF2 can predict the rate of progression of hepatic fat deposition, inflammation, and fibrosis in an individual, providing a basis for early intervention. Similarly, the occurrence of drug-induced liver injury (DILI) is closely related to an individual's genetic background. the CYP450 family of enzymes and HLA genotypes play key roles in drug metabolism and immune response, and can be used to identify high-risk patients, guide individualized medication use, and reduce the risk of drug-related liver injury.

In clinical treatment, precision medicine also promotes targeted therapy and personalized intervention. For example, for liver cancer patients with specific gene mutations, multi-targeted tyrosine kinase inhibitors (TKI) or immune checkpoint inhibitors can be selected to maximize efficacy and reduce unnecessary side effects. In addition, by combining multi-omics information with electronic health records and imaging data, disease management strategies can be further optimized to achieve a closed loop of early warning, dynamic monitoring and personalized intervention. Overall, precision medicine provides a systematic solution for liver diseases from risk prediction, early diagnosis to individualized treatment, and significantly improves clinical management.

2.3. Existing challenges

Although precision medicine has demonstrated great potential in the management of liver diseases, its clinical application still faces multiple challenges. The integration and analysis of multi-omics data is highly complex. Liver disease involves multidimensional information such as genomic, transcriptomic, proteomic, metabolomic and imaging data, and there are differences in the format, magnitude and noise of different types of data, so how to effectively integrate and extract clinically valuable features remains a technical challenge. In addition, the lack of standardized data collection and sharing mechanisms has limited the ability of cross-center research and model generalization, limiting the promotion and application of precision medicine results. The high cost of clinical translation is also a major obstacle. Multi-omics testing, data processing, computational analysis and implementation of individualized treatment plans all require high capital investment, as well as high requirements for professional teams, equipment and information systems. This problem is particularly acute in low- and middle-income countries or in healthcare organizations with limited resources, making it a real dilemma for precision medicine to spread globally. In addition, the lack of standardization and guidelines further limits the implementation of precision medicine. Most of the current guidelines for liver disease diagnosis and treatment are based on traditional clinical indicators and imaging assessments, and there is a lack of standardization for clinical interpretation of multi-omics data, individualized risk stratification, and therapeutic decision-making. There are significant differences in testing methods, marker thresholds and model evaluation criteria between different centers, making it difficult to directly translate research results into clinical practice. Ethics, privacy and data security issues also pose constraints on multi-center data sharing and clinical application.

3. Application of AI in precision diagnosis and treatment of liver diseases

3.1. Data types and algorithms

The application of AI in the precision diagnosis and treatment of liver diseases relies on multiple types of medical data and advanced algorithms. First, medical imaging is one of the most mature fields for AI application. Through the automated analysis of CT, MRI, ultrasound and other liver images by deep convolutional neural networks, AI can achieve lesion detection, segmentation and classification, and show high sensitivity and specificity in the early diagnosis and staging of liver cancer. For example, CNN models can identify tiny liver nodules and blood supply features, assisting radiologists in quantitative analysis and clinical decision-making, effectively improving diagnostic efficiency and consistency. Second, clinical electronic medical records provide rich patient information, including laboratory test results, medical history, drug usage and imaging reports. Machine learning-based models can mine potential laws from structured and unstructured data for disease risk prediction, efficacy assessment and individualized treatment plan recommendation. For example, algorithms such as Random Forest, Gradient Booster, and Support Vector Machine have been used to predict the risk of NAFLD/NASH disease progression and drug-induced liver injury. Third, the combination of multi-omics data integration and AI models is an important direction for precision medicine. By integrating genomic, proteomic, metabolomic and clinical imaging data, AI can capture the complex molecular features of diseases and realize the whole process management from early risk prediction to individualized intervention. Deep learning, graph neural networks and multimodal fusion models can process high-dimensional, nonlinear data to build comprehensive models for predicting the occurrence, progression and treatment response of liver diseases. This multilevel data integration not only improves the accuracy of the model, but also provides a scientific basis for individualized diagnosis and treatment, and provides technical support for the precise management of liver diseases.

3.2. Examples of clinical applications

The clinical application of AI in liver diseases has gradually moved from experimental research to practical assistance in decision-making. First of all, AI has shown significant potential in early diagnosis and staging of liver cancer. Image analysis models based on deep convolutional neural networks (CNN) can automatically identify small liver nodules in CT, MRI or ultrasound, and combine them with serum markers for risk assessment, realizing highly sensitive and specific detection. In addition, AI can assist in liver cancer staging by analyzing tumor size, morphology and blood supply characteristics to provide reference for surgical resection, radiofrequency ablation or interventional treatment options. In NAFLD/fatty liver risk prediction, machine learning models can effectively predict the risk of disease progression by combining clinical data, laboratory indicators and imaging features. Studies have shown that AI models are able to identify high-risk groups that are prone to progression to NASH or liver fibrosis, providing a scientific basis for early intervention and lifestyle management. This predictive ability is clinically valuable, especially in asymptomatic patients, enabling individualized prevention strategies. AI also shows significant potential for drug-induced liver injury (DILI). By integrating patient genotype information (e.g., CYP450 and HLA), drug metabolism profiles, and clinical data, machine-learning models can predict the risk of hepatic injury for a given patient's medications, thereby optimizing drug selection and dosing, and reducing the incidence of adverse events. Such personalized dosing regimens are particularly important in multidrug combinations or high-risk patients.

In addition, AI plays a role in adjunctive treatment regimen selection and prognostic assessment. By analyzing multi-omics data and clinical characteristics, AI models can simulate the potential effects of different treatment options on patients and assist physicians in developing optimal treatment strategies. At the same time, the model can dynamically track the patient's efficacy and recurrence risk, providing data support for long-term management and realizing accurate, closed-loop diagnosis and treatment.

3.3. Advantages

The application of artificial intelligence in the accurate diagnosis and treatment of liver diseases has multiple advantages, which significantly improves the diagnosis and treatment efficiency and individualization level. AI technology can improve diagnostic accuracy. While traditional imaging and laboratory tests are limited by physicians' experience and subjective judgment, deep learning models can accurately identify small lesions and early lesions through automated analysis of CT, MRI, ultrasound and other imaging data, improving the early diagnosis rate of liver cancer, NAFLD/NASH and other liver diseases. Meanwhile, AI can combine multi-omics data and clinical indicators to achieve risk prediction and disease typing, further enhancing the accuracy and scientificity of diagnosis.AI supports individualized intervention. By integrating patients' genetic information, metabolic characteristics and clinical data, AI can provide a fine-grained assessment of each patient's disease risk and provide a basis for early intervention, lifestyle adjustment and targeted therapy. For example, for NAFLD/NASH high-risk patients, AI can identify the likelihood of progression to liver fibrosis or hepatocellular carcinoma and guide individualized management strategies; in the management of drug-induced liver injury (DILI), AI can predict the patient's drug sensitivity, optimize the drug regimen, and reduce the risk of adverse events.

AI can accelerate clinical decision-making by analyzing large-scale clinical and multi-omics data to simulate the efficacy and risks of different treatments, thereby helping physicians develop faster, more scientific, and more consistent therapeutic plans, especially in complex scenarios such as liver cancer and multimorbidity management.

3.4. Limitations

Although AI shows great promise in the precision diagnosis and treatment of liver diseases, several challenges still hinder its full clinical translation and sustainable application. One of the most significant bottlenecks is data sharing and standardization. Liver disease–related clinical data originate from diverse sources, including imaging examinations, laboratory results, electronic medical records, and multi-omics analyses. However, variations in imaging equipment, acquisition protocols, laboratory testing methods, and annotation standards across different hospitals make it extremely difficult to construct large-scale, high-quality datasets with strong generalizability. These inconsistencies often lead to reduced model performance when AI systems are applied across centers, resulting in the "poor local adaptability" problem in real-world clinical environments. The lack of unified data management standards also restricts the development of multicenter collaboration and limits the depth and reliability of clinical validation.

Moreover, regulatory and ethical supervision remains a critical hurdle for medical AI. The use of AI in diagnostic and therapeutic decision-making involves sensitive personal health data and directly influences clinical outcomes, prompting countries and regions to impose strict requirements on data protection, model transparency, and system reliability. AI algorithms used in healthcare often must undergo medical device registration, regulatory review, and continuous auditing, while model updates must maintain compliance throughout their life cycle. Although these regulations are essential for ensuring patient safety, they increase the complexity, time investment, and operational cost of bringing AI technologies into routine clinical practice.

Additional challenges arise from the cross-border transmission of medical data, the need for ongoing model iteration, and the inherent uncertainty of predictive results. These issues require well-established ethical norms and robust regulatory frameworks to ensure that AI-assisted diagnostic systems operate in a transparent, safe, and controllable manner. Without clear governance, the widespread adoption of AI in liver disease management will remain difficult despite its significant potential.

4. Future development trend of AI and precision liver disease

4.1. Development trend of technology

As artificial intelligence continues to advance in medical research and clinical practice, its development in the precision diagnosis and treatment of liver diseases is becoming increasingly clear, particularly in imaging analysis, multimodal data integration, and interpretable models. Breakthroughs in deep learning–based radiomics have enabled early detection and precise assessment by extracting high-dimensional features from CT, MRI, and ultrasound images. Convolutional neural networks can automatically learn key liver imaging features, while attention mechanisms enhance recognition of complex or low-contrast lesions. In addition, graph convolutional networks effectively capture tumor heterogeneity and spatial relationships, promoting deeper understanding of tumor microenvironments. Multimodal data fusion has become a key trend in precision medicine for liver diseases, as disease progression is influenced by numerous factors that cannot be captured by a single indicator. By integrating imaging, laboratory tests, electronic medical records, and multi-omics data, AI can simultaneously "read images", "analyze biomarkers", and "interpret genetic profiles", enabling deeper characterization of disease biology. Such models improve the accuracy of NAFLD/NASH typing, early liver cancer risk prediction, and drug-induced liver injury susceptibility assessment. For example, combining imaging-detected steatosis with high-risk mutations like PNPLA3 or TM6SF2 yields more precise risk evaluation. With better data acquisition and computing power, multimodal fusion will continue to gain accuracy and generalizability.

In addition, interpretable AI has become increasingly important, as deep learning models often function as "black boxes" whose decision processes are difficult to understand. In clinical practice, physicians need clarity about the basis of a model's judgments to trust and apply its results. Interpretable techniques, such as feature-importance ranking and heatmap visualization, can highlight key image regions or clinical indicators used in diagnosis. For example, heatmaps can mark tumor-edge areas considered most relevant in liver cancer assessment. Such transparency enhances clinician–AI collaboration and improves acceptance in practice, while decision tree or rule-based components further translate model reasoning into human-understandable steps.

4.2. Clinical translation challenges

Although AI shows great promise in the precision diagnosis and treatment of liver diseases, several challenges still hinder its clinical translation. Data sharing and standardization remain major bottlenecks, as liver disease–related data originate from diverse sources and differ across hospitals in imaging protocols, testing methods, equipment types, and annotation quality. Such inconsistencies make it difficult to build high-quality, generalizable datasets and often lead to poor cross-center performance. In addition, regulatory and ethical constraints pose significant hurdles. Medical AI must comply with strict requirements regarding patient privacy protection, algorithm review, device registration, and model updates. These frameworks safeguard patient safety but increase development and deployment costs. Moreover, issues such as cross-border data flows, continuous model iteration, and uncertainty in predictive outputs require clear ethical guidelines and regulatory oversight to ensure transparency, safety, and controllability in clinical use.

Therefore, the establishment of perfect data standards, the promotion of the deep integration of medical and engineering disciplines, the construction of a cross-organizational cooperation platform, and the formation of a perfect regulatory system are the key steps to promote the true implementation of AI in the precision diagnosis and treatment of liver diseases. Only with the combined efforts of technology, regulations, ethics and clinical needs can AI play a greater role in the field of liver diseases and truly realize the leap from concept to application.

5. Conclusion

Artificial intelligence plays a key role in precision diagnosis and treatment of liver diseases, contributing significantly from early diagnosis and risk prediction to individualized treatment and prognosis assessment. By integrating imaging, clinical indicators and multi-omics information, AI realizes the data-driven diagnosis and treatment process, and improves diagnostic accuracy, targeted intervention and clinical decision-making efficiency. Despite the challenges of data standardization, cross-center generalization, regulation and ethical privacy, the combination of AI and multi-omics information still shows great potential for application. In the future, with the promotion of multimodal data fusion, interpretable AI, individualized closed-loop management and preventive interventions, AI is expected to be deeply integrated into the clinical practice of liver diseases, promoting the realization of precision medicine for a wider range of landings and applications, and providing patients with more efficient, safer, and individualized healthcare services.

Disclosure statement

The authors declare no conflict of interest.

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