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Application, Progress, Challenges and Coping Strategies of Artificial Intelligence in Laser Diagnosis and Treatment of Dermatology

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Abstract. Selective photothermolysis is the basic theoretical foundation of laser therapy, and now a highly used diagnostic and treatment method in dermatology is based on it. Although laser therapy has shown some good curative effects on various skin diseases, clinical application still faces many problems: the parameters are not standardized, the criteria for choosing them are inconsistent, the assessment of efficacy is mostly based on subjective visual checks, and dark-skinned people are more prone to adverse effects such as burns, pigment changes, etc. The general process and applications of artificial intelligence in laser dermatology will be introduced in this paper, such as pre-operative quantitative analysis of lesion images, intelligent adjustment of laser energy during surgery, and objective quantification of the effect of post-operative treatment. There are many serious problems in the actual operation that have not been solved yet; there is a lack of high-level clinical validation data, an opaque "black-box" mechanism for algorithms, data bias due to racial imbalance, a fragmented industrial supervision system, unreliable content hallucination from large language models, etc. The four problems that need to be solved in the new round of targeted countermeasures are large-scale multicenter cohort studies, the development of interpretable AI models, fair and standardised patient data privacy governance, and optimisation of human-machine collaborative clinical workflows. The aims of this paper are to offer theoretical support for the standardisation of clinical application of AI-assisted laser intervention and to help realise the goal of personalised and precise skincare.

Keywords: Artificial Intelligence, Dermatology, Laser Therapy, Precision Medicine, Interpretable AI

1. Introduction

Laser therapy has achieved some results in the treatment of pigmentary disorders, vascular malformations and aging skin diseases through selective photothermolysis. The old-school laser treatment is based on the experience of doctors, and there are many problems: It's hard to determine the appropriate parameters for each person; there are more risks of harm for people with dark skin; and it is difficult to objectively measure how well the treatment works. Therefore, there are problems with the uniformity of clinical effects and they cannot be applied widely in practice [1].

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With the development of deep learning and artificial intelligence, so too is the model of laser dermatology; now, it can be used for preoperative diagnosis and treatment plan design, real-time adjustment of surgical energy, data-driven monitoring of postoperative recovery progress, etc., and will be developed into highly precise intelligent control. Although AI-based laser therapy has shown some good results, it has not been widely used in China due to the lack of clinical evidence, a black-box model, unreasonable training data, etc [2]. This paper will introduce the current research status of artificial intelligence in laser dermatology, analyze the problems that need to be addressed, provide some ideas for development, and offer targeted solutions.

2. Historical evolution, clinical merits and limitations of laser therapy, and optimization via AI

Phototherapy and laser therapy are the cornerstones of modern dermatology and aesthetic medicine, and their development history can be shown in Figure 1.

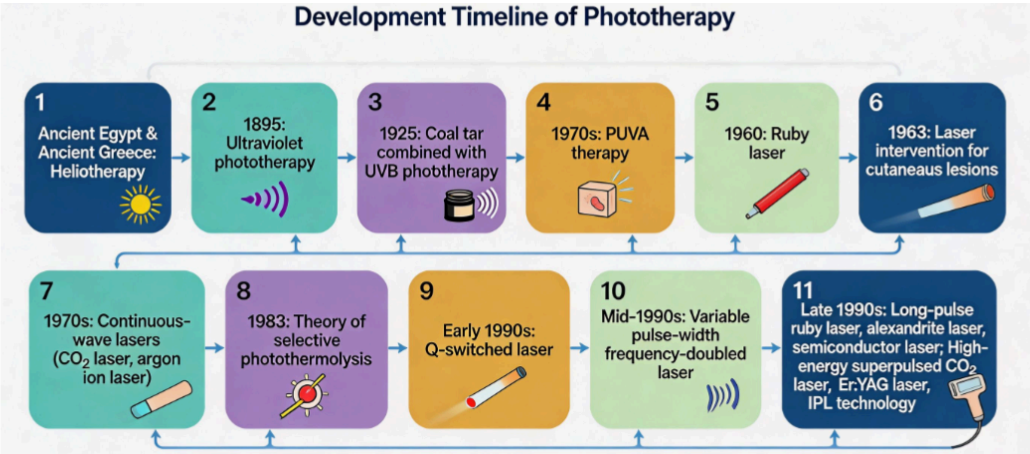

Figure 1. Development timeline of phototherapy

Laser treatment is now frequently used in dermatology to address many problems with pigmentary disorders, blood vessel abnormalities and scars, skin aging, benign tumours of the skin, etc. Selective photothermolysis can be used to target only the diseased area precisely and cause little damage; thus, it has been applied for a long time in treating pigmentation and blood vessel disorders as well as other aesthetic diseases. However, there are still some deficiencies in the current state: A large number of various parameters need to be individually optimised and extensive clinical experience is required; burns and pigmentary changes occur more frequently in people with dark skin; many rounds of treatment are necessary, and there are still issues with post-operative management and preventing recurrence [1]. As a result, new technologies have continuously been developed to address these problems, and now artificial intelligence, machine learning and deep learning are widely used in many areas of the beauty industry to promote the health of the skin.

Algorithms of artificial intelligence can be employed to automatically detect skin lesions in pictures of the skin. Big Data Training of Models Can Recommmend Individualised Laser Parameters for Treatment Plans. To help the patient recover better after surgery, the virtual assistant can remind them to take their medicine and follow other instructions on time [2]. Scaling up the integration of artificial intelligence and dermatological laser therapy is about to begin a new stage of precision, intelligence and personalised aesthetic medicine.

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3. AI-driven full-cycle laser therapy: preoperative precise assessment, intraoperative intelligent control, and postoperative quantitative follow-up

3.1. Preoperative AI imaging diagnosis and lesion evaluation

Precise Diagnosis of the Lesion can guide the design of a Laser Treatment plan. The old way of manual assessment is prone to human error and may not be able to find early-stage abnormalities early enough [3]. Artificial intelligence based on deep learning is now being employed to assist with the operation of laser surgery.

The foundation of AI assessment before the surgery is deep learning. CNN is used to extract morphological information from the images of lesions and differentiate between benign and malignant skin tumours [4]. With the help of the Transformer multimodal architecture, artificial intelligence can now predict the treatment plan according to the medical record and lesion image. Attention-based segmentation models can directly obtain the boundary and size of a lesion from the above objective data.

Artificial intelligence is used to conduct a kind of evaluation of preoperative examination data quantitatively and individually. Algos are used to determine how much to apply and how long to use the laser in skin and hair treatment therapy. Due to changes in the condition of the skin and in order to maintain the good health of other tissues, an intelligent system will adjust the treatment plan in time to avoid errors during laser operation [5].

3.2. Intraoperative robotic assistance and intelligent regulation

With the addition of artificial intelligence and laser control systems, changes in the direction of clinical application are expected; we will shift from experience-based manual operation to data-driven precision engineering management, and now they are being applied in all parts of surgical robots, such as timely control during surgery and flexible adjustment of energy, etc [6].

In order to solve the problem of rough-surface skin, teaching by demonstration and geometric constraint algorithms have been used to obtain normalised and reproducible motion trajectories for the robot based on clinical experience. With the help of integrated optical coherence tomography (OCT) closed-loop systems, robots can be placed a few micrometres away from the skin to avoid injury [7]. Six-degree-of-freedom aesthetic robots with multimodal vision have solved the problems of unstable position and uneven distribution of treatment in manual operation.

According to the actual data obtained from the operating room in real time, adjust the laser parameters and change the power output. The power of the laser hair removal and wound reconstruction platform will be changed automatically according to different conditions of the skin and injuries. Based on the training data, predictive models have been built to forecast how effective or harmful the treatment will be for a certain patient, predict the risk of adverse reactions, optimise laser parameters, and thus create an individualised treatment plan that is not the same as the general one [2].

3.3. Postoperative efficacy quantification and longitudinal follow-up

Typically, the signs that laser therapy has been successful are a lack of lesions and a happy patient; manually, it is not quantified [3]. Deep Learning and Generative AI can be employed to standardise the evaluation of post-operative health uniformly.

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AI models can compare the pictures of before and after cutting to determine the extent of scarring, changes in pigmentation and other alterations to the structure of the skin; due to a smaller probability of human error, they are also in line with clinical grades [8]. Based on the age, skin phototype and lesion shape of an individual, AI can predict whether they will be more responsive to treatment or have a risk of complications, and then offer a customised treatment plan.

Generative AI can predict what will happen to the patients after surgery and plan treatment accordingly. A remote intelligent imaging platform will be used to observe any changes in the lesion, and if there is a recurrence or other problems after surgery, the doctor will be informed; otherwise, he would need to go back to the hospital for follow-up care [9].

4. Practical dilemmas of AI in laser dermatology and systematic mitigation strategies

4.1. Deficient clinical evidence and barriers to evidence-based validation

Artificial intelligence has begun to be applied in laser dermatology, but a few clinical studies have not yet been published. Most of the current research is based on images, and there are few high-quality clinical trials of AI-assisted therapeutic planning [10]. Robotic Laser Systems are easy to operate and do not have many safety regulations. Standardisation of confounding factors such as skin type, model of laser equipment and experience of operators cannot be guaranteed in the conventional randomised controlled trial (RCT) design [11]. Due to changes in the actual light environment and various imaging equipment, the accuracy of the AI model will decline and the risk of diagnosis error will increase. Consumer-oriented AI skin analysis applications have not been conducted in clinical trials and are therefore not yet used in hospitals at present [12].

Countermeasures: Establish a few centre-based prospective clinical research consortia in different areas and standardise the core outcome sets and data collection procedures for various skin types and laser equipment. Standardise the lighting and imaging angles for taking the pictures, and thoroughly record the laser wavelength, energy density, pulse width, operator's qualification level, etc., to reduce technical differences [13]. Based on the results of the single-centre pilot RCT, carry out multi-centre confirmation trials using stratified block randomisation, centralised blinded assessment and adaptive trial design. Connect Controlled Trials and Routine Practice through the Framework of Real-World Evidence: Prospective Registry Studies have been used to address confounding factors by establishing external control cohorts, and Pragmatic Clinical Trials determine the additional clinical benefits. Federated Learning is for cross-population Model Generalisation. A bad event report and an early warning system will be set up to deal with them. Multi-centre accuracy tests of consumer-grade artificial intelligence tools in pathology should be conducted jointly with pathological gold-standard verification, and then randomised intervention studies can be organised to determine their clinical value [14].

4.2. Algorithmic black boxes and lack of model interpretability

Although deep learning architectures have achieved good results in the problem of lesion detection and laser regimen planning, they are black boxes that cannot be practically used in clinical practice [15]. At present, post-hoc interpretability tools are not practical for the field of dermatology, and doctors do not know why the model has reached that conclusion. Artificial intelligence is relatively sensitive to changes in light and also differs among many devices; as a result of a lack of concrete clinical guidelines and quantifiable risk factors, it has been out of regular use in hospitals and the

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government will soon change its view on the further clinical application of artificial intelligence technology [16].

Countermeasures: At all stages of the development of the full model, set interpretability requirements and add domain-specific dermatological constraints to the architectural Design. According to the concept bottleneck model, the feature representation in the hidden layer should align with clinical semantic descriptors, and the prototype learning network can construct reasons based on canonical lesion cases; the loss function penalizes deviations in the precision of spatial localisation [17]. According to the ExAID framework, a multimodal explanation engine will be constructed to combine imaging and clinical data, generate natural language descriptions, show visual attention heatmaps, etc., so that the results of the algorithm are in line with clinical reasoning. Some dimensions of the interpretability evaluation index have been established, such as decision fidelity, clinical adequacy, readability and boundary consistency, and these have been verified through clinician blind review, concept vector tests, causal intervention experiments, etc [18]. Test the stability of the explanations provided by the model in different light conditions and at various settings for all modules. Interpretability indices should be added to the standard diagnostic performance indicators for clinical certification and use of new drugs.

4.3. Ethical, legal and regulatory challenges

4.3.1. Data bias and health equity

There is a systematic representation bias in the existing AI training data; it does not have enough data from dark-skinned individuals and thus has poor performance in diagnosing darker skin types. The bias is due to an imbalance in data collection and algorithm structure, and it is also caused by the subjective aesthetic standards of cosmetic dermatology that are different among different races and skin tones [19].

Countermeasures: Build globally representative cutaneous imaging databases that are stratified according to skin phototype and supplement them with resampling and generative adversarial network (GAN) synthetic data to address the problem of insufficient data for the dark-skin group [20]. Carry out full-life-cycle fairness audits of algorithms: Rebalance and resample the data by reweighting and resampling at the data level to achieve a balanced distribution of skin tones; add equity constraints to model training in adversarial debiasing and fair representation learning; post-hoc validation should report the performance of subgroups according to race and skin phototype in a stratified manner. According to the scores from experts, patient-reported outcome scales and other objective quantitative biomarker data will be used to build a multi-dimensional aesthetic grading system, and then aesthetic fairness constraints will be added to the model training workflow. Establish a pre-market verification of the fairness and generalisability of different skin tones [21].

4.3.2. Liability allocation and legal accountability

Artificial intelligence in medical diagnosis and therapy has significantly changed the old medical liability system, and it has not yet been decided who will be held responsible for AI misdiagnosis or erroneous treatment recommendations. The traditional "tool liability" theory is unable to address the new problems of algorithm autonomy, black-box models and human-machine collaboration, etc., which have created many new responsibilities for various subjects and made causal analysis extremely difficult [22]. Another problem is that the beauty shown in AI does not align with the realistic appearance after disease.

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Countermeasures: Build a multi-tier, risk-based liability division plan and keep the undisturbed, all-record AuditTrail of the whole process. The system will store the original model output, confidence interval and dataset version of every decision made with the help of AI, and clinicians need to record a structured reason for accepting or rejecting the AI recommendation together with their biometric signature to form an audit trail [23]. Based on the level of AI automation, a multi-tier liability system will be formed: Advisory-tier AI will be subject to the previous medical standards, and the main responsible subjects will be the institution and the physician; Collaborative-tier AI will be subject to a presumption of joint liability for algorithm developers and medical institutions, and physicians will need to carry out their own audits, etc.; algorithms of fully autonomous laser systems will be regarded as quasi-liable subjects, and developers and supporting institutions will be strictly liable under special medical malpractice insurance. Judicial Supervision should be expanded to cover the legal evaluation of the model's explainability, and feature ranking and counterfactual explanations need to lighten the burden of proof in cases of malpractice [24]. Standardise the mandatory disclosure procedures for aesthetic predictive simulations, clarify the scope of uncertainty and the speed of predictive bias, add such disclosures to the statutory informed consent form to clarify the rights and obligations of both doctors and patients.

4.3.3. Data privacy, cybersecurity and fragmented regulation

As a result, AI cutaneous analysis tools collect a large number of facial and lesion images of patients and are therefore under the strict regulations of medical privacy laws [25]. Generative AI hallucinations can be used to generate false pathological signs and fake comorbidities that are harmful to the health of patients and thus fall under the scope of medical malpractice lawsuits. At present, the regulatory standards around the world are still developing unevenly, and very few AI-based dermatological devices have been officially approved for use in China; there is also no specific supervision for AI laser therapy. As there has been relatively little research on the effects and risks of unsupervised consumer-facing mobile artificial intelligence applications, prompt regulation is necessary [26].

Countermeasures: To safeguard the privacy of medical information for patients, it is proposed that, by coupling horizontal federated learning with homomorphic encryption and trusted execution environments, model training can be carried out without transferring raw data or gradients. Use the knowledge graph of dermatology to correct hallucinations in generative AI and use retrieval-augmented generation (RAG) at the same time to ensure the accuracy of the information. Build a multi-level human-in-the-loop supervision system for clinical practice, require that all reports and therapeutic suggestions produced by artificial intelligence must include their confidence scores and references to peer-reviewed clinical evidence, and need to be verified by doctors before being officially applied [27]. Automatically block the high-risk erroneous output and create a permanent audit log of the low-confidence or rare-case prediction. At the level of regulation, unify the evaluation and certification standards for AI medical devices in China and abroad, and classify the risk of AI laser platforms according to the degree of automation. Mandate Multi-centre Registry Trials for Market Authorisation and Compulsory Post-market Surveillance. Consumer-facing AI skin applications should be classified as Class II or higher medical devices, and cross-phototype accuracy and all-around safety data sets must be provided; they should have clear user interface disclosures that the regulatory approval status and documented performance limitations are subject to periodic recertification audits [28].

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4.4. Potential, limitations and clinical application strategies of large language models

Although LLMs can be used to help inform patients about healthcare, optimise clinical work, construct initial treatment plans for laser dermatology, etc., they are not yet perfect; that is to say, the accuracy of diagnosis is lower than that of specialist doctors, specific laser parameters (such as wavelength and energy density) cannot be provided, and hallucinations may still occur, which could lead to incorrect clinical directions and harm for patients [29].

Countermeasures: Use LLMs to support the three-tier collaborative model for decision-making; have them conduct the initial screening, and then clinicians will independently judge the results and work together to decide on the treatment path. LLMs can generate an organised first draft of the differential diagnosis, a graded treatment plan, evidence citations and confidence scores, and then clinicians will revise and verify each part [30]. If the confidence score of the output is low or it is a rare skin disease, it will be automatically selected for mandatory review by a human expert to ensure that the final clinical diagnosis is made by a doctor.

A specialised LLM can be built technically, and then fine-tuned based on the clinical guidelines of dermatology; at the same time, a retrieval-augmented generation module will be added to link with standardised laser dosimetry databases to reduce hallucinations and speculative output. Set up a particular hallucination detection pipeline to verify the numerical treatment parameters and device specifications, and if there is any unsupported content in the audit log, raise an alarm. An ensemble method is employed to determine the threshold of predictive uncertainty, and high-risk treatment recommendations will not be put into practice in actual therapy [31].

5. Conclusion

Laser therapy uses the principle of selective photothermolysis and is one of the current ways dermatologists treat skin diseases, but it is still a practice with many arbitrary parameters and subjective assessment of effects; it is also relatively high-risk for people with darker skin. Artificial intelligence has been applied to the entire process of diagnosis, pre-treatment planning, laser therapy, monitoring of treatment outcomes after laser treatment, etc., to create a new model of personalised dermatology based on data.

Although AI-assisted laser therapy has been used widely in clinics, several problems have not yet been solved; that is to say, there is a lack of multi-centre clinical trial data, the algorithms are non-transparent "black boxes", there is a risk of racial data bias and uneven treatment, international regulations for medical devices vary greatly, and large language models are prone to hallucination. The corresponding solutions are a stratified cohort trial, development of domain-specific interpretable AI, privacy-preserving fair data governance, tiered liability framework, physician-led human-machine collaborative workflow, etc.

In the future, interdisciplinary research will also be carried out in dermatology, laser technology and artificial intelligence. Standardisation of validation, fair distribution of data, transparent algorithms and united supervision will allow us to make better use of artificial intelligence power in building safe, personalised and equitable precision laser therapy for all people.

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