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Research on the Application of 3D Printing Technology in Surgical Clinical Training and Rare Disease Treatment

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Abstract

3D printing technology is penetrating into every corner of the medical field, serving as an innovative driving force for surgical clinical training and rare disease treatment. With the help of 3D printing technology, it is possible to intuitively understand the anatomical structure of the relevant parts of patients, conduct surgical simulation training, and assist in formulating personalized treatment plans. This article reviews the application of 3D printing technology in surgical clinical training and rare disease treatment, and discusses its development limitations and future directions.

Keywords

3D Printing Technology; Simulation Model; Surgical Clinical Training; Rare Disease Treatment.

1. INTRODUCTION

In today's digital age, 3D printing technology, as a disruptive innovative manufacturing process, is penetrating into every corner of the medical field at an unprecedented speed. Based on digital models, it integrates computer processing and reconstruction technologies, and flexibly uses diverse materials such as metals, ceramics, and polymers to precisely stack and construct solid objects layer by layer. It is also known as additive manufacturing technology[1]. Through 3D printing technology, it is possible to simulate natural tissue structures, extracellular matrix components, and vascular structures in vitro, creating bionic structures that play a crucial role in researching cell-cell interactions, disease mechanisms, clinical teaching, and applications. In surgical clinical training, it can quickly and accurately print 3D anatomical simulation models based on the real imaging data of patients, providing medical students with an intuitive, three-dimensional, and tangible learning tool. This helps them to comprehensively familiarize themselves with the anatomical features of the surgical site, simulate surgical procedures in advance, significantly shorten the learning curve, and improve the proficiency and accuracy of surgical operations. In the field of rare disease treatment, 3D printing can customize suitable medical devices, implants, and drug formulations according to the personalized anatomical structures and pathological features of patients, achieving precision medicine. It can also construct realistic pathological models to assist doctors in deeply analyzing the condition, opening up a new path for overcoming rare disease problems.

2. ANALYSIS OF THE CURRENT SITUATION OF SURGICAL CLINICAL TRAINING AND RARE DISEASE TREATMENT

2.1. Development Status and Requirements of Surgical Clinical Training

Surgery is a highly practical applied science that emphasizes the improvement of clinical capabilities through practice. The main purpose of surgical clinical training and teaching is to enhance the clinical skills of trainees, with a focus on assessing their practical and operational abilities[2]. In recent years, teaching methods for surgical clinical training have developed rapidly. Novel teaching methods have emerged, including problem-based learning(PBL), case-based learning(CBL), and flipped classrooms. With the rapid development of Internet plus, technologies such as robot-assisted and three-dimensional endoscope system video-assisted have made significant progress in clinical surgeries, and have also contributed to the innovation of clinical training and teaching methods. Establishing teaching based on precise virtual reality simulators is an effective way to improve the clinical surgical capabilities of young doctors. In addition, in recent years, the pace of interdisciplinary integration has accelerated. Surgical clinical training is no longer limited to single-subject surgical knowledge but is integrated and infiltrated with imaging, pathology, physiology, psychology, etc., to establish a complete knowledge system, thereby strengthening doctors' accurate diagnosis of diseases and rational design of treatment plans.

Traditional surgical clinical training involves practicing on animal substitutes or cadavers, combined with learning from surgical videos and on-site surgical teaching. However, due to the differences between animal substitutes and human structures and the lack of soft tissues, blood vessels, and nerve tissues in cadaver teaching aids, trainees cannot fully understand and master the knowledge and operation essentials. Moreover, learning from surgical videos and on-site surgical teaching is limited to observation, and there is no linkage among learning, hands-on practice, and reflection.

2.2. Complexity of Rare Diseases and Limitations of Traditional Treatments

Rare diseases, as extremely challenging problems in the medical field, are incredibly complex. The World Health Organization defines rare diseases as "diseases or disorders that affect between 0.65‰ and 1‰ of the total population"[3]. There are many types of rare diseases, which are sporadic, diverse, and complex. Although significant progress has been made in the identification, diagnosis, and treatment of rare diseases in the past, the current medical systems, both internationally and domestically, still struggle to meet the diagnostic and treatment needs of rare diseases[4]. 80% of rare diseases are caused by gene-coding errors, leading to mutations or genetic gene defects, resulting in congenital genetic diseases, tumors, nervous system diseases, etc. Traditional treatment methods often have limitations when dealing with rare diseases. For example, in the case of congenital scoliosis combined with syringomyelia, the patient's spine not only has an unusual curvature, but the vertebral bones are irregular in shape. Moreover, the location, size, and shape of the syrinx in the spinal cord vary, and its relationship with surrounding nerves and blood vessels is intricate. This unique anatomical structure anomaly poses a great challenge to traditional imaging diagnoses. Two-dimensional X-rays and CT scans are difficult to fully display the details of the lesions, and although magnetic resonance imaging(MRI) can provide more soft-tissue information, it still has limitations in presenting complex spatial structural relationships. Doctors find it difficult to accurately grasp the full picture of the condition, which brings many difficulties to the formulation of subsequent treatment plans. The surgical treatment process also has problems. The lack of precise preoperative planning tools means that when facing the complex and variable anatomical structures of rare-disease patients on the operating table, doctors lack foolproof coping strategies. The surgical risks and the incidence of postoperative complications increase significantly, and the patient's postoperative situation is also not optimistic.

3. ANALYSIS OF THE ADVANTAGES OF 3D PRINTING TECHNOLOGY

As a new material manufacturing method, 3D printing technology has continuously undergone technological innovation in the past two decades and has been widely used in the medical field for tissue modeling, surgical plan design and training for tumors and other

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surgeries, prosthesis manufacturing, clinical teaching, etc. Based on 3D digital models, this technology uses the methods of layer-by-layer manufacturing and superposition to stack materials, making it a new type of digital technology. The printed models have a good sense of spatial three-dimensionality, restoring the shape of the lesion and the surrounding blood vessels in a 1:1 ratio, which is convenient for subsequent teaching and disease treatment[5].

3.1. Construction of High-Fidelity Surgical Models

Using high-fidelity surgical models for teaching and training is an effective way to improve clinical surgical capabilities. Simulation models can eliminate the harm caused by mistakes due to unfamiliarity with the anatomical structure. The advantages of simulation models in visually and three-dimensionally displaying anatomical models play a positive role in helping trainees learn basic anatomical structures and practice anatomical operations. At the same time, non-biological teaching aids have a positive impact on reducing psychological stress, increasing learning interest, and improving learning efficiency. Simulation models support repeated operations and practices, which can further enhance trainees' confidence and accumulate operational experience[6].

3D printing technology converts abstract two-dimensional images into intuitive, three-dimensional, and tangible physical models based on the imaging data of patients' diseased tissues, achieving the visualization of rare diseases and providing effective assistance for the treatment of rare diseases. This can reduce the incidence of complications and mortality during the patient's surgical period. Taking tetralogy of Fallot(TOF), a congenital heart disease, as an example, the 3D-printed heart simulation model can accurately present key information such as the location and shape of the ventricular septal defect, the degree of aortic overriding, the shape of the right ventricular outflow tract stenosis, and the abnormal development of the pulmonary valve. Based on the simulation model, doctors can observe the heart structure from multiple angles before surgery, deeply understand the details of the lesions, and formulate detailed surgical plans. At the same time, the simulation model also makes the doctor-patient communication more efficient.

3.2. Improvement of Training Effect and Efficiency

Due to the unbalanced teaching resources and the lack of unified standards for training methods in different regions and medical institutions, there are significant differences in surgical training. The application of 3D printing technology provides an effective solution to this problem, strongly promoting the standardization and homogenization of surgical training. On the one hand, 3D-printed models are made based on unified medical imaging data standards and modeling specifications. The accurately reproduced human anatomical structures and pathological features of the models provide standardized learning samples for training and teaching activities. On the other hand, 3D-printed models, combined with detailed operation guidelines and teaching videos, form a complete standardized training system, which plays a positive role in aligning the training quality of different medical institutions and narrowing the training level gap.

3.3. Optimization of Surgical Planning and Pre-operation Rehearsal Process

3D printing technology can present the patient's anatomical structure in the form of a physical model, greatly enhancing the surgical team's intuitive understanding of the patient's individual characteristics. This helps to break through the limitations of traditional two-dimensional images. Through the simulation model, doctors can examine the surgical site from multiple angles, identify potential surgical risks in advance, and provide a more reliable basis for formulating personalized surgical plans. Taking neurosurgery as an example, the brain structure is complex, with nerves and blood vessels intertwined. Subtle differences can lead to significantly different surgical results. By 3D-printing a patient's simulated cranial model, doctors can accurately measure the distance between the tumor and surrounding important nerves and blood vessels, clearly observe the distribution of cerebral blood vessels, such as the diameter, curvature of the anterior, middle, and posterior cerebral arteries and their branches, and the spatial relationship with the surrounding brain tissue. This enables doctors to plan the position, size, and angle of the surgical incision based on accurate data during training, avoid important blood vessels and nerves in advance, and reduce damage to surrounding normal nerve and blood vessel tissues. At the same time, in practice, doctors can use the model to repeatedly practice operations, familiarize themselves with the operation space and angles of surgical instruments in the complex cranial structure, greatly improving the accuracy and proficiency of medical students' surgical operations, and thus ensuring the patient's life and health.

3.4. Customized Treatment Plans

The design of customized treatment plans is another significant advantage of 3D printing technology. For patients with rare skeletal malformation diseases, abnormal ossification occurs during the growth of their bones, resulting in joint stiffness and limited limb movement. Using 3D printing technology, osteotomy guides and orthopedic implants can be designed according to the real-time state of the patient's bones, ensuring the accuracy of the osteotomy position and angle and the close fit between the implant and the bone, bringing new hope for the restoration of the patient's limb function.

4. APPLICATION OF 3D PRINTING TECHNOLOGY IN SURGICAL CLINICAL TRAINING

In 2020, the People's Hospital of Zhejiang Province was approved as a national training base for gastroesophageal reflux surgery. Professor Wang Zhifei, director of the Multidisciplinary Diagnosis and Treatment Center for Gastroesophageal Reflux Disease at the hospital, successfully presided over a training project on 3D-printed models for simulating robot-assisted anti-reflux surgery. Before that, foreign countries used minimally invasive laparoscopic fundoplication for gastroesophageal reflux disease, but this technology was relatively new to Chinese surgeons, and few surgeons had mastered it. Professor Wang Zhifei's team conducted research through computer simulation and bioinformatics methods, creating 3D-printed dry-laboratory models to simulate anti-reflux surgery scenarios. Simulating actual operations with real surgical instruments helps to improve the learning curve of robot-assisted Nissen fundoplication from early laboratory training to clinical application. This technology enables more surgeons to master techniques such as Nissen fundoplication and is a cutting-edge technology for anti-reflux surgery training. It has received funding from the key research and development projects of the Ministry of Science and Technology of China.

The All India Institute of Medical Sciences in New Delhi, India, uses Stratasys 3D printing technology to develop cranial base neurosurgery simulators for craniotomy and neuroendoscopic surgery. High-fidelity multi-textured models are specifically made for surgical planning and training, ensuring that neurosurgeons can clearly observe the anatomical structure. The neuroendoscopic trainer is based on a pick-and-place mechanism, equipped with flat and tilted movable plates with rubber inlet ports, as well as a 2D digital display screen and a camera system. Using standard neuroendoscopes with variable angles, it provides a process for practicing surgeries under different levels of visual feedback, helping surgeons understand the relevant complex anatomical structures, master relevant techniques, and evaluate the feasibility when performing simulation steps, while avoiding any risks to patients.

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5. APPLICATION OF 3D PRINTING TECHNOLOGY IN RARE DISEASE TREATMENT

The Cleveland Clinic, the largest cardiovascular disease cardiac surgery center in the United States, collaborated with New York University Abu Dhabi to use advanced 3D printing technology to create a 3D model of the heart for a 41-year-old patient with a rare cardiovascular disease and develop a complex surgical plan. The patient had a congenital aortic defect with a Kommerell's diverticulum and a large aneurysm. His aorta arched to the right after leaving the heart(normally it arches to the left). The global incidence of Kommerell's diverticulum combined with a right aortic arch is only 0.03%. The patient's right aortic arch masked the defect of the Kommerell's diverticulum with other large blood vessels, increasing the difficulty of surgical intervention. In this case, the use of a 3D-printed model greatly improved the safety of the surgery and allowed for more precise and customized surgeries. The application process of 3D printing technology is divided into three stages: the 3D image reconstruction stage, which creates a 3D model based on the original diagnostic imaging data, providing a digital framework for the patient's anatomical structure; the 3D slicing stage, which conducts a detailed analysis of individual structures and organs; and the 3D printing stage, which generates a physical replica of the patient's anatomical structure for surgeons to examine and use for preoperative planning and simulation.

The Fourth Department of Orthopedics of the People's Hospital of Liaoning Province used 3D printing technology to enable a patient with a rare bone tumor to walk independently. The patient had a tumor on the right calcaneus, and there were multiple tumor lesions on the right fibula and right toe bones. A biopsy of the tumor site was diagnosed as Ollier disease(multiple enchondromas), a rare non-genetic disease with a low incidence. The traditional surgical treatment plan required the resection of the entire tumor-bearing bone. However, in order not to affect the patient's postoperative independent walking, reconstructing the calcaneus was a difficult problem. The shape of the prosthesis replacing the calcaneus not only needed to match the surrounding bone, but the prosthesis joint surface also needed to form a stable fusion with the adjacent bone in the long-term to ensure the patient's walking ability after surgery. Conventional prostheses could not solve this problem. The team of the Fourth Department of Orthopedics established a model based on the patient's calcaneus CT data, used 3D printing technology to design and print a calcaneus prosthesis that highly matched the adjacent bone, and installed a polyethylene cushion at the bottom of the prosthesis to protect the plantar soft tissues and reduce the patient's discomfort when walking after surgery. Sixteen months after the surgery, the patient came for a review while walking independently. The 3D-printed calcaneus prosthesis was in a good position, and there were signs of bone ingrowth from the surrounding bone on the surface of the prosthesis, achieving the expected surgical results.

6. SUMMARY

Based on previous research, this article analyzes the advantages of 3D printing technology and its applications in surgical clinical training and rare disease treatment. 3D printing technology has greatly enriched medical training methods and effectively promoted the development of the medical industry. Compared with traditional medical and training models, it provides highly realistic models and low-cost training opportunities, achieving remarkable results in improving training effects, assisting in clinical surgical diagnosis and planning, and enhancing treatment effects. Compared with traditional treatment methods, 3D printing technology has great potential. However, in the future, there is still a long way to go in selecting suitable manufacturing materials, reducing material costs and time costs, and improving the degree of simulation. It is necessary to develop matching simulation models and standardized courses for different training stages, design operation detection platforms, shorten the talent

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training cycle, and improve the training quality. In the field of rare disease treatment, how to integrate cutting-edge technologies such as gene therapy and cell therapy and deeply promote interdisciplinary integration is the research direction for clinical applications.

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