Application of Three-Dimensional Reconstruction Technique in Percutaneous Kyphoplasty

Deqiang Gao[1], Xiaobo Guo[2,*], Dengsheng Guo[1]

[1] Changzhi Medical College, Changzhi 046000, Shanxi, China

[2] Spine Minimally Invasive Orthopedics Department, Jincheng General Hospital, Jincheng 048000, Shanxi, China

DOI: 10.32629/jcmr.v5i4.3124

Abstract: At present, the aging process of the population in China has been gradually accelerated, and the incidence of osteoporosis in patients with thoracolumbar fractures in China is also increasing year by year. With the increasing elderly, compression fractures caused by osteoporosis are one of the important factors of thoracolumbar fractures. Vertebral fractures are most common in the T12 vertebral body, L1 vertebral body, L2 vertebral body, etc. , and most patients have no obvious trauma or only mild trauma, such as sprains, bending down and other daily movements, which can easily lead to vertebral fractures. The treatment of vertebral fractures is divided into conservative or surgical treatment, which is generally performed according to the patient's condition (1). Although conservative treatment is relatively safe, it is difficult to achieve satisfactory clinical efficacy, limiting its clinical application. Surgical treatment has a significantly higher clinical outcome than conservative treatment, and has been widely used by surgeons for the treatment of vertebral compression fractures in the elderly (2). Surgical treatment mainly includes percutaneous kyphoplasty (PKP) and percutaneous vertebroplasty (PVP), and both methods have the characteristics of easy operation, less trauma, and fewer complications. After PVP/PKP in patients with osteoporotic compression fractures of the vertebrae at T12 and L1 levels, increasing bone mineral density (BMD) of the adjacent lumbar spine increased vertebral strength and decreased the incidence of adjacent vertebral fractures, and PKP was superior to PVP in increasing BMD of the adjacent lumbar spine (5). PKP is superior to PVP in terms of the amount of injected cement, short-term pain relief, improvement of short-term and long-term kyphotic angles, and reduction of cement leakage rate (6). In clinical practice, there are many types of patients with thoracolumbar vertebral compression fractures caused by osteoporosis, with large individual differences, so it brings many problems for its diagnosis, evaluation, and treatment (7). Three-dimensional reconstruction technique is a new imaging technique developed in recent years. It combines CT, MRI, X-ray and other imaging techniques with computer image processing, so as to make the display of the internal structure of the vertebral body and the fracture line clearer and provide more intuitive image information for clinical surgery. This article reviews the application of three-dimensional reconstruction technique in PKP treatment before, after and data analysis.

***Keywords*:** lumbar compression fracture; finite element; mimics software; three-dimensional reconstruction; percutaneous kyphoplasty

1. Introduction

In the field of modern medicine, with the rapid development of imaging technology, three-dimensional reconstruction technology (3D reconstruction) has become one of the important tools of precision medicine, especially in the field of spinal surgery has shown great application potential. Percutaneous kyphoplasty (PKP), as a minimally invasive treatment technique, has been widely used to treat osteoporotic vertebral compression fractures (OVCFs) with the aim of stabilizing the spine, relieving pain, and restoring vertebral body height. However, the success of surgery often depends on accurate preoperative evaluation and planning, as well as precise intraoperative operation. In this context, the application of three-dimensional reconstruction technology in PKP surgery is particularly important because of its unique advantages.

Three-dimensional reconstruction techniques can accurately reconstruct the three-dimensional structure of objects or scenes by analyzing and processing two-dimensional images taken from different perspectives. The core idea is to deduce the three-dimensional structure of the target object through two-dimensional image information from different perspectives using the principle of Multi-view Geometry. In PKP surgery, three-dimensional reconstruction technology can not only provide three-dimensional images of the diseased vertebral body, so that doctors can intuitively and comprehensively understand the lesion, but also perform accurate surgical planning and simulation before surgery, laying a solid foundation for the successful implementation of surgery.

Specifically, three-dimensional reconstruction techniques can help physicians accurately assess the degree of vertebral

compression, fracture type, and anatomical relationship of surrounding tissues in patients, resulting in personalized surgical plans. In the preoperative planning stage, the doctor can perform the simulation operation on the three-dimensional model, such as simulating the screw placement position, angle and depth, simulating the osteotomy correction, etc., so as to optimize the surgical path and reduce the surgical risk. In addition, three-dimensional reconstruction technology can also assist doctors to predict the effect of surgery, evaluate the height recovery and stability of the postoperative vertebral body, and provide a more scientific and reasonable treatment plan for patients.

In summary, the application of three-dimensional reconstruction technique in percutaneous kyphoplasty not only improves the accuracy and safety of the operation, but also promotes the rapid recovery of patients after surgery. The aim of this paper is to investigate the application status, advantages and future development direction of three-dimensional reconstruction technology in PKP surgery, in order to provide a reference for clinical practice and scientific research in the field of spinal surgery.

2. Application of three-dimensional reconstruction technique in preoperative evaluation of PKP

With the development of computer and three-dimensional reconstruction technique, for patients with vertebral fracture, three-dimensional reconstruction technique can more accurately display the degree of vertebral compression, peripheral ligament injury, etc., providing more intuitive images for clinical diagnosis, facilitating intraoperative localization of the lesion segment, thus providing an important basis for the selection and implementation of surgical plan.

The medical image processing software mimics is often used to generate, edit and process three-dimensional images, etc., and it can complete a large number of data conversions on personal computers, thereby achieving rapidity and further reducing the time for modeling [8-9]. Mimics is mainly used for medical tomography image data processing. This is a highly integrated and easy-to-use software for three-dimensional image creation and processing [10]. It can scan medical X-ray, CT, MRI and other images to obtain data and construct 3D models. Modeling is mainly composed of the following five modules: the base module includes image import, image segmentation, image visualization, image registration, and image measurement [11].

In actual clinical operation, due to individual differences or the complexity of compression fractures, physicians can use three-dimensional reconstruction technology to perform preoperative evaluation for patients with special conditions and understand the situation in the surgical area before surgery, so as to develop a more suitable surgical approach, cement injection volume and diagnosis and treatment plan for this patient, reduce the invasiveness of surgery and simplify the surgical process to reduce the possible risks and failure rate during surgery.

3. Application of three-dimensional reconstruction technique in PKP

In PKP, doctors need to fully understand the anatomy of the vertebral body and develop a reasonable surgical plan according to the specific circumstances of patients. Based on this data collected by Yan Jianwen et al. [12], Mimics was used to simulate the treatment and establish a three-dimensional geometric model, and the effectiveness of model loading was verified. They used three-dimensional reconstruction techniques to simulate clinical hyperextension reduction maneuvers using different treatment methods and analyzed changes in stress and displacement at different parts of the injured vertebral body. Zhang Xun, Chen Tiantian et al. [13] established different forms of bone cement models by three-dimensional reconstruction technique, and obtained the target model by combining the bone cement model and the vertebral body model. The stress changes of the vertebral body and annulus fibrosus of the adjacent segments under different cement injection modes and injection volumes were summarized under bending, extension and it was determined that only selecting the best puncture site and appropriate bone cement injection volume could reduce the stress of the adjacent segment structure.

Therefore, the finite element model was developed and analyzed to find the most appropriate cement morphology and injected volume. In the finite element model, kyphoplasty, placement of artificial bone or bone cement, and internal fixation can also be added for different personalized lumbar fractures, and biomechanical changes of the vertebral body can also be simulated, and then the stability of the vertebral body after surgery can be assessed (14).

Tang Long et al. [15] used three-dimensional reconstruction technique to assist PKP surgery in the treatment of lumbar vertebral compression fractures, and the accuracy of surgical localization and the success rate of surgery were significantly improved. Mou Gang et al. [16] treated lumbar vertebral compression fractures by PKP surgery assisted by three-dimensional reconstruction technique not only shortened the operation time but also reduced the occurrence of postoperative complications, and obtained very satisfactory clinical results.

Yang Fuguo et al. [17] discussed the use of Mimics to simulate preoperative puncture and screw placement, so as to obtain the best surgical path and puncture trajectory and other related surgical parameters, based on which virtual simulation surgery can not only make the surgical operation more accurate, but also reduce the difficulty of surgery and unnecessary

iatrogenic injury, so as to obtain better and safer clinical efficacy.

In summary, three-dimensional reconstruction technology can provide intraoperative localization and navigation and can be used to assist clinicians in surgical procedures. The intraoperative navigation system is mainly composed of computer-assisted navigation system, positioning device, imaging equipment and operator. Computer-assisted navigation system mainly through three-dimensional reconstruction technology to obtain preoperative image data and transform into a model, and these data model into surgical navigation system. This technique can accurately locate the patient on the basis of preoperative planning according to the image data and the patient's anatomy, and through the model, the physician can better understand the patient's fracture vertebral body shape and convexity, avoiding the blindness of traditional surgery. Simulate the operation process on a computer, determine the operation path, use a balloon to reduce and repair the fractured vertebral body, and then inject bone cement for filling. In this simulation, the injection volume of bone cement can be more accurate, so as to prevent the second injury caused by the leakage of bone cement in the postoperative recovery period. The system can record the image information during the operation, such as the volume of spinal canal, the shape of diseased vertebral body and other information, and can correct and correct in the virtual environment. Through the simulation of model and operation, the physician can combine with the actual operation scenario to avoid accidental injury to the surrounding tissues and nerves.

4. The role of three-dimensional reconstruction technique in the postoperative outcome of PKP

Through preoperative and postoperative CT, MRI and intraoperative X-ray and other imaging data, three-dimensional reconstruction technology was applied to evaluate the postoperative recovery of patients. Guo Hui et al. [18] well described the appropriateness of biomechanics through finite element simulation mechanical analysis, which could provide sufficient mechanical stability at the fracture end. Xiao Yu et al. [19] used finite element analysis software to analyze the maximum stress and stress turbidity map data of the fracture site and implant, and used finite element method to analyze the stress distribution and changes of the fracture site and implant. It was concluded that the uneven stress between the fracture site and the implant would lead to poor stability of the fracture site and increased possibility of implant sliding or even fracture.

After PKP treatment, patients with increased vertebral body height had a significantly lower risk of severe vertebral fractures, and had faster postoperative recovery and shorter hospital stays. Finite element analysis can be used for bone stress analysis; this is key to assessing fracture risk, understanding bone remodeling, and designing fracture fixation devices. Finite element analysis helped to determine the percentage of strain in each patient after surgery [20]. Thus, patients requiring revision could be identified when the strain percentage did not match the preset micro-motion range.

However, only some studies have reported the clinical results of patients before and after surgery, and the postoperative follow-up results of these patients are not consistent. Wang Germany et al. [21] successfully established a finite element thoracolumbar model and calculated the number of layers of each operated vertebral body to obtain different cement perfusion and distribution patterns. It is suitable not only for studying biomechanical changes after simulated cement injection, but also for studying biomechanical changes when different materials are applied to the spine. It lays a foundation for the development of new materials and technologies.

Quan Yongli et al. [22] established a three-dimensional model by collecting the image data of patients undergoing PKP surgery for 1 month, and analyzed the model, thus verifying the effect of functional exercise recovery after PKP surgery, and obtaining a good postoperative recovery effect and spinal stability effect of PKP. Three-dimensional reconstruction can be used to evaluate postoperative imaging results and stress results, so as to better guide clinicians to select the subsequent treatment plan.

5. Application of three-dimensional reconstruction technology in data analysis

Three-dimensional reconstruction technique can more comprehensively understand the morphological changes of vertebral body, the recovery of postoperative vertebral body height and the compression fracture of adjacent segments through multi-angle and multi-directional observation. Yao Jie et al. [23] used Mimics software to measure the spinal anatomy, and compared the surgical and computer-assisted anatomical measurements. The results showed that computer-assisted spine anatomy measurement based on Mimics software had higher accuracy and reliability compared with surgical anatomy measurement.

Liu Liangfeng et al. [24] established a more intuitive and real three-dimensional image using CT three-dimensional reconstruction technology, which not only made up for some shortcomings of traditional CT, but also provided comprehensive information on lumbar fracture segments, including the direction of fracture line and the displacement direction of fracture fragments, which can stereoscopically present the anatomical structure for doctors to measure so as to develop a surgical plan

and postoperative efficacy evaluation to provide a basis.

Chen Zhiyong et al. [25] found that the volume in three-dimensional reconstruction technology showed the overall image in the current technology, without the need to determine the surface. It is a three-dimensional spatial anatomical relationship existing in the original data, and it can effectively distinguish vascular and non-vascular structures.

Yang Qingjue et al. [26] tried to implement the generation of confrontation network (GAN) model for automatic isotopic image conversion of the spine, which has the potential for clinical application in routine examinations. It is hoped that from a novel perspective, better deep learning models and multicentric conduction will be achieved through low-cost, faster, high-quality, and accurate three-dimensional spinal reconstruction.

6. Outlook

Three-dimensional reconstruction provides more accurate images and information for PKP surgery and plays a key role in the success rate and safety of surgery. In addition, three-dimensional reconstruction technology can also help clinicians to individualize the design and improve the efficiency of surgery. With the application of 3D printing in medicine, the future of additive manufacturing (AM) in trauma orthopedic surgery is relatively bright [27]. Bioprinting in this area will focus on fractures, nonunions, deformities, and bone, cartilage, and soft tissue reconstruction. This innovative technology not only helps medical staff, but also benefits patients because medical problems that used to be incurable can now be solved by modern technology.

With increasing evidence and clinical experience, we believe that three-dimensional reconstruction techniques will become an available tool in the routine preoperative phase and be applied to more complex surgical cases in which they have been shown to have a crucial role. However, it is important to consider current limitations and the practical utility of such techniques [28]. The main limitation in implementing 3D reconstruction techniques is the high cost. In addition, the implementation of these techniques requires coordination with other personnel.

Three-dimensional reconstructions are not without limitations. First, model quality inherently depends on image quality. That is, the image acquisition mode has a direct impact on the final quality of the results. Because three-dimensional reconstruction is affected by image quality, computation time and consumption of computing resources, the available computing power should also be considered for any improvement in imaging resolution [29]. Although three-dimensional reconstruction technology has certain clinical applications, it has not been widely used in clinical practice, the main reason is that three-dimensional reconstruction technology is expensive and not suitable for all spinal surgeons, and secondly, in practical clinical practice, patients pay more attention to functional improvement results such as pain relief.

The future development direction should be to develop three-dimensional reconstruction software with low cost and simple operation, so that it is more popular and easy to use. With the development of medical imaging technology, three-dimensional reconstruction technology will have a broader application prospect. It is believed that with the deepening of relevant basic research and clinical practice, three-dimensional reconstruction technology will be widely used in the field of PKP.

Acknowledgments

Fund Project: Health Commission of Shanxi Provincial's "Four Batches" Science and Technology Driven Medical Innovation Plan (No. 2021XM39).

References

[1] LIN J., QIAN L., JIANG C.,et al. Bone cement distribution is a potential predictor to the reconstructive effects of unilateral percutaneous kyphoplasty in OVCFs: a retrospective study. Journal of Orthopaedic Surgery and Research. 2018 Jun 7;13(1):p. 140.

[2] LIU M, CHEN XT, DOU T, et al. Surgical treatment of back pain in patients with osteoporotic thoracolumbar vertebral compression fractures. Chongqing Medicine 2017; 46: 2419–2421, 2430 [In Chinese].

[3] HINDE K., MAINGARD J., HIRSCH J. A., et al. Mortality outcomes of vertebral augmentation (vertebroplasty and/or balloon kyphoplasty) for osteoporotic vertebral compression fractures: a systematic review and meta-analysis. Radiology. 2020 Apr;295(1):96–103.

[4] NORIEGA D., MACIA S., THEUMANN N., et al. A prospective, international, randomized, noninferiority study comparing an implantable titanium vertebral augmentation device versus balloon kyphoplasty in the reduction of vertebral compression fractures (SAKOS study) The Spine Journal. 2019 Nov;19(11):1782–1795.

[5] Zhang C, Zhu K, Zhou J, et al. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi. 2013;27(7):819-823.

[6] Wang H, Sribastav SS, Ye F, et al. Comparison of Percutaneous Vertebroplasty and Balloon Kyphoplasty for the

Treatment of Single Level Vertebral Compression Fractures: A Meta-analysis of the Literature. Pain Physician. 2015;18(3):209-222.
[7] COMPSTON JE, MCCLUNG MR, LESLIE WD. Osteoporosis. Lancet. 2019;393(10169):364–376.
[8] Wang Jiao, Liu Yang, Zhang Xiaoling, etc Application of Mimics software in 3D reconstruction of medical images [J]. Chinese Medical Equipment Journal,2015,36(02):115-118.
[9] Wang Gui, Zhang Zhi, Zhang Liang, etc Application and Experience of Mimics Digital Software in Clinical Orthopedic Teaching Work [J]. China Medical Education Technology,2014,28(05):527-529.
[10] HU X.-J., WANG H. Biomechanical assessment and 3D finite element analysis of the treatment of tibial fractures using minimally invasive percutaneous plates. Experimental and Therapeutic Medicine. 2017;14(2):1692–1698.
[11] WAN S, XUE B, XIONG Y. Three-Dimensional Biomechanical Finite Element Analysis of Lumbar Disc Herniation in Middle Aged and Elderly. J Healthc Eng. 2022 Jan 15;2022:7107702.
[12] YAN J, LIAO Z, YU Y. Finite element analysis of dynamic changes in spinal mechanics of osteoporotic lumbar fracture. Eur J Med Res. 2022 Aug 6;27(1):142.
[13] ZHANG X, CHEN T, MENG F, et al. A finite element analysis on different bone cement forms and injection volumes injected into lumbar vertebral body in percutaneous kyphoplasty. BMC Musculoskelet Disord. 2022 Jun 28;23(1):621.
[14] Wang Jian, Li Kai, Chen Bo et al. Establishment and analysis of three-dimensional finite element model for thoracolumbar vertebral compression fractures [J]. Orthopedic Journal of China,2016,24(16):1498-1503.
[15] Tang Long, Yang Bo, Zhang Bo et al. Clinical Application of Digital Orthopedics in Minimally Invasive Treatment of Severe OVCF [J]. China Digital Medicine,2015,10(01):61-63.
[16] Mou Gang, Ren Weijian. Application of preoperative 3D reconstruction CT scan in vertebral body shaping surgery [J]. Clinical Journal of Medical Officers,2016,44(10):1003-1005.
[17] Yang Fuguo Clinical study of Mimics 3D visualization technology combined with minimally invasive spinal locator [D]. Guangzhou Medical University,2017.
[18] GUO H, LI J, GAO Y, et al. A Finite Element Study on the Treatment of Thoracolumbar Fracture with a New Spinal Fixation System. Biomed Res Int. 2021 Apr 10;2021:8872514.
[19] YU X, RONG PZ, PANG QJ, et al. The Effect on the Fracture Healing following Femoral Neck Shortening after Osteoporotic Femoral Neck Fracture Treated with Internal Fixation: Finite Element Analysis. Biomed Res Int. 2021 Aug 4;2021:3490881.
[20] El-DESOUKY MA, SALEH AA, AMR SM, et al. Finite element analysis modeling of plates versus intramedullary nails in closed comminuted midshaft tibial fractures. SICOT J. 2022;8:26.
[21] WANG D, LI Y, YIN H, et al. Three-dimensional finite element analysis of optimal distribution model of vertebroplasty. Ann Palliat Med. 2020;9(3):1062-1072.
[22] Kuai Yongli Clinical efficacy and finite element analysis of postoperative PKP combined with lumbar and back muscle exercise [D] Yunnan University of Chinese Medicine,2018.
[23] YAO J, DONG B, SUN J, et al. Accuracy and Reliability of Computer-aided Anatomical Measurements for Vertebral Body and Disc Based on Computed Tomography Scans. Orthop Surg. 2020 Aug;12(4):1182-1189.
[24] Liu Liangfeng, Yan Jingang. Clinical value analysis of multi-slice spiral CT three-dimensional reconstruction applied in the diagnosis of lumbar spine fractures [J] Journal of Medical Imaging,2014,24(03):492-494.
[25] Chen Zhiyong, Wang Wenzhen The clinical application value of CT three-dimensional bone reconstruction in lumbar spine fracture surgery [J]. China & Foreign Medical Treatment,2018,37(24):188-190.
[26] YANG CJ, LIN CL, WANG CK, et al. Generative Adversarial Network (GAN) for Automatic Reconstruction of the 3D Spine Structure by Using Simulated Bi-Planar X-ray Images. Diagnostics (Basel). 2022 Apr 30;12(5):1121.
[27] ZAMBORSKY R, KILIAN M, JACKO P, et al. Perspectives of 3D printing technology in orthopaedic surgery. Bratisl Lek Listy. 2019;120(7):498-504.
[28] PORTNOY Y, KOREN J, KHOURY A, et al. Three-dimensional technologies in presurgical planning of bone surgeries: current evidence and future perspectives. Int J Surg. 2023;109(1):3-10. Published 2023 Jan 1.
[29] FITZPATRICK X, FAYZULLIN A, WANG G, et al. Cells-in-Touch: 3D Printing in Reconstruction and Modelling of Microscopic Biological Geometries for Education and Future Research Applications. Bioengineering (Basel). 2023 Jun 5;10(6):687.

Author Bio

First author: Deqiang Gao; Male; 1993; pursuing a master's degree (Class 2203); Resident physician; Research direction: Orthopedics; E-mail: 654104066@qq.com

Corresponding author: Xiaobo Guo; Male; 1982; Doctor; Deputy chief physician; Research direction: Orthopedics; E-mail: bobo4310@163.com