3D 打印技术在骨科领域的应用进展

周涵薇,陈涛,杜伟斌,何丽红,全仁夫

(杭州市萧山区中医院,浙江　杭州　311201)

摘　要　3D 打印技术是一种快速成型技术,近年来该技术在骨科领域逐渐被广泛应用。本文对 3D 打印技术在骨科医疗器械制造、骨组织工程和再生医学研究、骨科解剖模型制作中的应用进展进行了综述,并对 3D 打印技术在骨科领域的待完善之处进行了总结。

关键词　打印,三维;医院,骨科;骨疾病/医疗器械;组织工程;再生医学;人体模型;综述

3D 打印技术是一种快速成型技术,其主要通过计算机辅助设计软件的分层处理技术构建 3D 结构实体模型[1]。Hull 等于 1984 年首次报道了一种名为立体平版印刷的技术,并于 1986 年获得该技术的专利,同年采用该技术打印了三维实体模型,这标志着 3D 打印技术的诞生[2]。3D 打印技术可通过铺设连续的物体材料层来创建独特的架构,因此近年来在医学领域逐渐被广泛应用,如制作医疗器械、创建生物模型或生物复制品、研发药物制剂等[2-3]。3D 打印技术在骨科领域的应用日益增多,既往主要用于制备个性化人工关节等,近年来常用于制定手术计划、制作解剖模型等。本文就 3D 打印技术在骨科领域的应用进展综述如下。

1　3D 打印技术在骨科医疗器械制造中的应用

采用 3D 打印技术制作的骨科医疗器械种类较多,常见的有手术器械、矫形器和植入物 3 种。

1.1　手术器械　目前,采用 3D 打印技术制作的骨科手术器械主要有手术导航模板、手术刀、牵开器、组织钳和止血器等[4-6]。采用 3D 打印技术制作的手术器械在骨科临床的用途较广,如用于骨质疏松性脊柱骨折[7]、骨盆截骨[8]、关节置换[9-11]、椎间盘切除[12]、骨肿瘤切除[13-15]、骶髂关节融合[16]、脊柱畸形矫正[17]、肩胛骨骨折[18]、肘关节切开复位[19]和颅骨成形[20]等手术中。采用 3D 打印技术制作的手术器械精度较高、更符合患者的解剖特征,尤其适合进行特定的骨科手术。此外,3D 打印技术可以根据新型材料的特征制作医疗器械,能够通过改良医疗器械的形状、重量等改善手术预后。

1.2　矫形器　矫形器又称支架,多用于四肢或脊柱,具有预防或矫正畸形、辅助或替代肢体功能等作用[21]。由于矫形器是一种与人体密切接触的器具,其个性化设计尤为重要。与采用 3D 打印技术制作的矫形器相比,传统的矫形器存在一些缺陷。例如:石膏夹板,长时间固定容易造成压疮、骨筋膜室综合症、肢体僵硬等[22];低温热塑板,制作过程相对复杂,且外观不佳,弃用率较高;高温热塑板,制作周期较长[23]。由于采用 3D 打印技术制作的矫形器更符合患者的局部解剖特点,其佩戴矫形器的舒适度较高,且 3D 打印技术制作矫形器的时间相对较短,有助于降低制作成本[24-25]。

1.3　植入物　多数骨科手术会用到植入物,但传统植入物多存在大小不合适等问题。3D 打印技术能够根据手术需要及局部解剖特点精确设计植入物形状,可以减少术后植入物松动、移位等并发症[26-27]。Tatara等[28]研究发现,采用 3D 打印技术制作的骨组织可以良好修复绵羊大面积缺失的下颌骨,由此认为可采用 3D 打印技术制作人体骨组织,以此治疗自体骨缺损。Yao 等[29]研究发现,采用 3D 打印技术制作的内固定钢板可以与不规则骨良好匹配,能够使应力均匀分布,有助于避免应力集中造成的植入物断裂。

2　3D 打印技术在骨组织工程和再生医学研究中的应用

2.1　骨组织工程　组织工程支架是骨组织工程的重要组成部分。理想的组织工程支架应具有生物相容性、可降解性、生物活性和高连通性,以利于营养物质

基金项目:国家自然科学基金项目(81904053);浙江省医药卫生科技计划项目(2020KY797);浙江中医药大学附属医院科研专项(2021FSYYZY43)

通讯作者:杜伟斌　E-mail:dwbbdm@163.com

和代谢物质的扩散[30-34]。组织工程支架传统的制备方法较多,如溶液浇铸、冷冻干燥、气体发泡和静电纺丝等,均有孔隙率不佳等不足之处。采用 3D 打印技术制作的组织工程支架,具有较高的孔隙率,且可化学降解[35]。Koffler 等[36]将采用 3D 打印技术制作的水凝胶支架植入小鼠脊髓损伤部位,发现该支架具有良好的生物相容性,且可促进轴突再生,由此认为采用 3D 打印技术制作的仿生支架可为脊髓损伤患者早期进行神经干细胞移植提供条件。

2.2　再生医学　3D 打印技术在骨科再生医学中的应用,目前主要是制作个性化自体软骨,以此修复软骨缺损。膝关节软骨损伤临床较为常见,病情严重时可导致膝关节疼痛及功能障碍[37]。但是膝关节软骨却没有足够的自我修复能力[38]。Shi 等[39]采用 3D 打印技术制作出结构与功能优化的丝素明胶支架,该支架的主要成分包括丝素蛋白、明胶及骨髓间充质干细胞亲和肽,因为该支架可为骨髓间充质干细胞的增殖和分化提供合适的微环境,所以该支架可用于修复软骨损伤。

3　3D 打印技术在骨科解剖模型制作中的应用

3D 打印技术可以根据患者的解剖特点制作相应的解剖模型,该模型的用途较广,如制定术前计划、病例讨论及医学教学等。采用 3D 打印技术制作的解剖模型有助于各种术前评估活动的顺利进行[40]。Morgan 等[41]研究发现,在骨科创伤手术的术前计划中使用 3D 打印技术制作相关模型,可以缩短手术时间、减少术中出血量和透视次数。采用 3D 打印技术制作的解剖模型对于医生治疗罕见病也有帮助。X 线、CT 等影像学检查并不能完全反映人体局部的结构和特征,因此可通过 3D 打印技术制作特定的解剖模型,进一步加深医生对患者病情的认识,从而制定个性化的治疗方案[42-43]。3D 打印技术不仅可用于制作解剖模型,还可用于医学教育。与教科书上和计算机上的 3D 解剖模型相比,采用 3D 打印技术制作的解剖模型更加直观,有助于医学生更好地掌握解剖学内容。此外,还可采用 3D 打印技术制作低成本的手术操作模型,如经口气管插管模型[44]、缝合模型[45]、腹腔镜操作模型[46]等,这些模型为医学生提供了相对真实的手术操作经验。由于患者的文化水平和理解能力存在差异,术前沟通的难易度也不同。临床可以患者的影像学检查图片为基础,采用 3D 打印技术制作个性化模型,以此向患者介绍其病情及治疗方案,有助于加深其理解,从而使医患沟通更加容易[47-49]。

4　3D 打印技术在骨科领域的待完善之处

虽然 3D 打印技术为骨科医生制定手术方案提供了更多选择,也为患者选择个性化治疗方案提供了便利,但该技术仍存在待完善之处。采用 3D 打印技术制作的植入物成本较高、制作周期较长,患者不容易接受。后期处理是 3D 打印技术的一个重要步骤,但后期处理的操作相对复杂,不仅延长了制作时间,且增加了制作成本。我们认为,未来可通过改良打印材料或技术来简化 3D 打印技术的后期处理。最佳的骨科 3D 打印材料应具备无毒、力学性能好、生物相容性高等特点,因此打印材料的革新是提高 3D 打印技术的关键。目前可用于 3D 打印的生物材料相对有限,且一些新型的生物材料尚处于实验阶段,因此研发新型 3D 打印生物材料是亟待解决的问题。采用 3D 打印技术制作的模拟手术模型与真实手术操作存在差异,这可能影响手术的准确性。以 3D 打印切割模具为例,由于 CT 三维重建图像不能完全反映骨膜及骨骼周围软组织的厚度,切割模具的放置位置可能受影响,术中需要切开更多的软组织进行定位。采用 3D 打印技术制作的植入式医疗设备目前尚无统一的行业标准,且部分设备的制作技术尚不成熟。此外,目前有关 3D 打印医疗器械的标准化问题仍然存在[50]。

5　小　结

近年来 3D 打印技术在骨科领域的应用逐渐增多,该技术不仅为医生的手术操作提供了便利,也为患者的个性化治疗提供了可能。然而,一些采用 3D 打印技术制作的医疗器械从制备到获得监管部门批准的时间较长,无法应用于急危重症患者。此外,在生物医学领域,采用 3D 打印技术制作的人体器官是否会面临与克隆技术相同的伦理问题,目前尚无定论。

参考文献

[1] WANG C,LAI J,LI K,et al. Cryogenic 3D printing of dual-delivery scaffolds for improved bone regeneration with enhanced vascularization[J]. Bioact Mater,2020,6(1):137-145.

[2] KHAJAVI S H,PARTANEN J,HOLMSTROM J. Additive manufacturing in the spare parts supply chain[J]. Comput Ind,2014,65(1):50-63.

[3] KERMAVNAR T,SHANNON A,O'SULLIVAN K J,et al. Three-dimensional printing of medical devices used di-

rectly to treat patients:a systematic review[J]. 3D Print Addit Manuf,2021,8(6):366 – 408.

[4] LONG C,LIU J H,CHAI X P,et al. A novel 3D-printed device for precise percutaneous placement of cannulated compression screws in human femoral neck fractures[J/OL]. Biomed Res Int,2021,2021:1308805[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/34222465/.

[5] FALDINI C,MAZZOTTI A,BELVEDERE C,et al. A new ligament – compatible patient – specific 3D – printed implant and instrumentation for total ankle arthroplasty:from biomechanical studies to clinical cases[J]. J Orthop Traumatol,2020,21(1):16.

[6] MARENGO N,MATSUKAWA K,MONTICELLI M,et al. Cortical bone trajectory screw placement accuracy with a patient – matched 3 – dimensional printed guide in lumbar spinal surgery:a clinical study[J]. World Neurosurg,2019,130:e98 – e104.

[7] SIU T L,ROGERS J M,LIN K,et al. Custom – made titanium 3 – dimensional printed interbody cages for treatment of osteoporotic fracture – related spinal deformity[J]. World Neurosurg,2018,111:1 – 5.

[8] WANG X,LIU S,PENG J,et al. Development of a novel customized cutting and rotating template for Bernese periacetabular osteotomy[J]. J Orthop Surg Res,2019,14(1):217.

[9] SULTAN A A,MAHMOOD B,SAMUEL L T,et al. Cementless 3D printed highly porous titanium – coated baseplate total knee arthroplasty:survivorship and outcomes at 2 – year minimum follow – up[J]. J Knee Surg,2020,33(3):279 – 283.

[10] PATEL H,KINMON K. Revision of failed total ankle replacement with a custom 3 – dimensional printed talar component with a titanium truss cage:a case presentation[J]. J Foot Ankle Surg,2019,58(5):1006 – 1009.

[11] SUN M L,ZHANG Y,PENG Y,et al. Accuracy of a novel 3D-printed patient-specific intramedullary guide to control femoral component rotation in total knee arthroplasty[J]. Orthop Surg,2020,12(2):429 – 441.

[12] YANG H S,PARK J Y. 3D printer application for endoscope-assisted spine surgery instrument development:from prototype instruments to patient – specific 3D models[J]. Yonsei Med J,2020,61(1):94 – 99.

[13] PARK J W,SHIN Y C,KANG H G,et al. In vivo analysis of post – joint – preserving surgery fracture of 3D – printed Ti – 6Al – 4V implant to treat bone cancer[J]. Bio – Des Manuf,2021,4(4):879 – 888.

[14] JOVICIC M Š,VULETIC F,RIBICIC T,et al. Implementation of the three – dimensional printing technology in treatment of bone tumours:a case series[J]. Int Orthop,2021,45(4):1079 – 1085.

[15] WEI F,LI Z,LIU Z,et al. Upper cervical spine reconstruction using customized 3D – printed vertebral body in 9 patients with primary tumors involving C2[J]. Ann Transl Med,2020,8(6):332.

[16] PATEL V,KOVALSKY D,MEYER S C,et al. Prospective trial of sacroiliac joint fusion using 3D – printed triangular titanium implants[J]. Med Devices (Auckl),2020,13:173 – 182.

[17] GARG B,GUPTA M,SINGH M,et al. Outcome and safety analysis of 3D – printed patient – specific pedicle screw jigs for complex spinal deformities:a comparative study[J]. Spine J,2019,19(1):56 – 64.

[18] WAN S X,MENG F B,ZHANG J,et al. Experimental study and preliminary clinical application of mini – invasive percutaneous internal screw fixation for scaphoid fracture under the guidance of a 3D – printed guide plate[J]. Curr Med Sci,2019,39(6):990 – 996.

[19] SHE R F,ZHANG Y,ZHANG B,et al. An individualized intra – articular stabilization device designed based on 3D printing technology for traumatic instability of the ulnohumeral joint[J/OL]. Biomed Res Int,2020,2020:3056395[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/33294437/.

[20] LANNON M,ALGIRD A,ALSUNBUL W,et al. Cost – effective cranioplasty utilizing 3D printed molds:a canadian single – center experience[J]. Can J Neurol Sci,2022,49(2):196 – 202.

[21] MANFREDI L,CAPOCCIA E,CIUTI G,et al. A soft pneumatic inchworm double balloon(spid)for colonoscopy[J]. Sci Rep,2019,9(1):11109.

[22] DELASOBERA B E,PLACE R,HOWELL J,et al. Serious infectious complications related to extremity cast/splint placement in children[J]. J Emerg Med,2011,41(1):47 – 50.

[23] CHA Y H,LEE K H,RYU H J,et al. Ankle – foot orthosis made by 3D printing technique and automated design software[J/OL]. Appl Bionics Biomech,2017,2017:9610468[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/28827977/.

[24] BARRIOS – MURIEL J,ROMERO – SÁNCHEZ F,ALONSO – SÁNCHEZ F J,et al. Advances in orthotic and prosthetic manufacturing:a technology review[J]. Materials (Basel),2020,13(2):295.

[25] HALE L,LINLEY E,KALASKAR D M. A digital workflow

for design and fabrication of bespoke orthoses using 3D scanning and 3D printing,a patient – based case study[J]. Sci Rep,2020,10(1):7028.

[26] 赵庆红,郭俊卿,高琰,等.3D打印技术在医疗领域的应用价值与展望[J].机械设计与制造工程,2018,47(6):1 – 5.

[27] ANGELINI A,KOTRYCH D,TROVARELLI G,et al. Analysis of principles inspiring design of three – dimensional – printed custom – made prostheses in two referral centres[J]. Int Orthop,2020,44(5):829 – 837.

[28] TATARA A M,KOONS G L,WATSON E,et al. Biomaterials – aided mandibular reconstruction using in vivo bioreactors[J]. Proc Natl Acad Sci U S A,2019,116(14):6954 – 6963.

[29] YAO Y,MO Z,WU G,et al. A personalized 3D – printed plate for tibiotalocalcaneal arthrodesis:design,fabrication,biomechanical evaluation and postoperative assessment[J/OL]. Comput Biol Med,2021,133:104368[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/33864971/.

[30] SULTAN S,MATHEW A P. 3D printed porous cellulose nanocomposite hydrogel scaffolds[J/OL]. J Vis Exp,2019(146)[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/31081812/.

[31] HUANG B,HU R,XUE Z,et al. Continuous liquid interface production of alginate/polyacrylamide hydrogels with supramolecular shape memory properties[J/OL]. Carbohydr Polym,2020,231:115736[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/31888822/.

[32] LI S,WANG K,HU Q,et al. Direct – write and sacrifice – based techniques for vasculatures[J/OL]. Mater Sci Eng C Mater Biol Appl,2019,104:109936[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/31500055/.

[33] OVSIANIKOV A,KHADEMHOSSEINI A,MIRONOV V. The synergy of scaffold – based and scaffold – free tissue engineering strategies[J]. Trends Biotechnol,2018,36(4):348 – 357.

[34] GONZALEZ – FERNANDEZ T,RATHAN S,HOBBS C,et al. Pore – forming bioinks to enable spatio – temporally defined gene delivery in bioprinted tissues[J]. J Control Release,2019,301:13 – 27.

[35] SCHWARTZ R,MALPICA M,THOMPSON G L,et al. Cell encapsulation in gelatin bioink impairs 3D bioprinting resolution[J/OL]. J Mech Behav Biomed Mater,2020,103:103524[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/31785543/.

[36] KOFFLER J,ZHU W,QU X,et al. Biomimetic 3D – printed scaffolds for spinal cord injury repair[J]. Nat Med,2019,25(2):263 – 269.

[37] HU X,WANG Y,TAN Y,et al. A difunctional regeneration scaffold for knee repair based on aptamer – directed cell recruitment[J/OL]. Adv Mater,2017,29(15)[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/28185322/.

[38] CHEN P,ZHENG L,WANG Y,et al. Desktop – stereolithography 3D printing of a radially oriented extracellular matrix/mesenchymal stem cell exosome bioink for osteochondral defect regeneration[J]. Theranostics,2019,9(9):2439 – 2459.

[39] SHI W,SUN M,HU X,et al. Structurally and functionally optimized silk – fibroin – gelatin scaffold using 3d printing to repair cartilage injury in vitro and in vivo[J/OL]. Adv Mater,2017,29(29):1701089[2022 – 04 – 09]. https://pubmed. ncbi. nlm. nih. gov/28585319/.

[40] ZHENG Y X,YU D F,ZHAO J G,et al. 3D printout models vs. 3D – rendered images:which is better for preoperative planning?[J]. J Surg Educ,2016,73(3):518 – 523.

[41] MORGAN C,KHATRI C,HANNA S A,et al. Use of three-dimensional printing in preoperative planning in orthopaedic trauma surgery:a systematic review and meta – analysis[J]. World J Orthop,2020,11(1):57 – 67.

[42] SILBERSTEIN J L,MADDOX M M,DORSEY P,et al. Physical models of renal malignancies using standard cross-sectional imaging and 3 – dimensional printers:a pilot study[J]. Urology,2014,84(2):268 – 272.

[43] 储传敏,刘溪,潘秀武,等.3D打印联合术中超声在腔镜下治疗完全内生型肾肿瘤中的应用(附15例报告)[J].第二军医大学学报,2017,38(8):1065 – 1070.

[44] PARK L,PRICE – WILLIAMS S,JALALI A,et al. Increasing access to medical training with three – dimensional printing:creation of an endotracheal intubation model[J]. JMIR Med Educ,2019,5(1):e12626.

[45] GALLAGHER P O,BISHOP N,DUBROWSKI A. Investigating the perceived efficacy of a silicone suturing task trainer using input from novice medical trainees[J]. Cureus,2020,12(1):e6612.

[46] PARKHOMENKO E,YOON R,OKHUNOV Z,et al. Multi-institutional evaluation of producing and testing a novel 3D-printed laparoscopic trainer[J]. Urology,2019,124:297 – 301.

[47] ATALAY H A,ÜLKER V,ALKAN I,et al. Impact of three-dimensional printed pelvicaliceal system models on residents ́understanding of pelvicaliceal system anatomy before percutaneous nephrolithotripsy surgery:a pilot study[J]. J Endourol,2016,30(10):1132 – 1137.

（下转第59页）

[23] LU K,LI H Y,YANG K,et al. Exosomes as potential alternatives to stem cell therapy for intervertebral disc degeneration: in-vitro study on exosomes in interaction of nucleus pulposus cells and bone marrow mesenchymal stem cells[J]. Stem Cell Res Ther,2017,8(1):108.

[24] LI H,TIAN L,LI J,et al. The roles of circRNAs in intervertebral disc degeneration: inflammation, extracellular matrix metabolism, and apoptosis [J/OL]. Anal Cell Pathol (Amst),2022,2022:9550499[2022-05-09]. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8856834/

[25] GUO Z,QIU C,MECCA C,et al. Elevated lymphotoxin-α (TNFβ) is associated with intervertebral disc degeneration[J]. BMC Musculoskelet Disord,2021,22(1):77.

[26] LUO L,JIAN X,SUN H,et al. Cartilage endplate stem cells inhibit intervertebral disc degeneration by releasing exosomes to nucleus pulposus cells to activate Akt/autophagy[J]. Stem Cells,2021,39(4):467-481.

[27] CHENG X,ZHANG G,ZHANG L,et al. Mesenchymal stem cells deliver exogenous miR-21 via exosomes to inhibit nucleus pulposus cell apoptosis and reduce intervertebral disc degeneration[J]. J Cell Mol Med,2018,22(1):261-276.

[28] SUN Y,ZHANG W,LI X. Induced pluripotent stem cell-derived mesenchymal stem cells deliver exogenous miR-105-5p via small extracellular vesicles to rejuvenate senescent nucleus pulposus cells and attenuate intervertebral disc degeneration[J]. Stem Cell Res Ther,2021,12(1):286.

[29] SAKAI D,MOCHIDA J,IWASHINA T,et al. Differentiation of mesenchymal stem cells transplanted to a rabbit degenerative disc model: potential and limitations for stem cell therapy in disc regeneration[J]. Spine(Phila Pa 1976),2005,30(21):2379-2387.

[30] XIE L,CHEN Z,LIU M,et al. MSC-derived exosomes protect vertebral endplate chondrocytes against apoptosis and calcification via the miR-31-5p/ATF6 axis[J]. Mol Ther Nucleic Acids,2020,22:601-614.

[31] LI Z Q,KONG L,LIU C,et al. Human bone marrow mesenchymal stem cell-derived exosomes attenuate IL-1β-induced annulus fibrosus cell damage[J]. Am J Med Sci,2020,360(6):693-700.

[32] XIA C,ZENG Z,FANG B,et al. Mesenchymal stem cell-derived exosomes ameliorate intervertebral disc degeneration via anti-oxidant and anti-inflammatory effects[J]. Free Radic Biol Med,2019,143:1-15.

[33] LYU F J,CUI H,PAN H,et al. Painful intervertebral disc degeneration and inflammation: from laboratory evidence to clinical interventions[J]. Bone Res,2021,9(1):7.

[34] ZHANG Z,ZHANG L,YANG J,et al. Influence of extracellular nanovesicles derived from adipose-derived stem cells on nucleus pulposus cell from patients with intervertebral disc degeneration[J]. Exp Ther Med,2021,22(6):1431.

[35] ZHU L,SHI Y,LIU L,et al. Mesenchymal stem cells-derived exosomes ameliorate nucleus pulposus cells apoptosis via delivering miR-142-3p: therapeutic potential for intervertebral disc degenerative diseases [J]. Cell Cycle,2020,19(14):1727-1739.

[36] ZHANG J,ZHANG J,ZHANG Y,et al. Mesenchymal stem cells-derived exosomes ameliorate intervertebral disc degeneration through inhibiting pyroptosis [J]. J Cell Mol Med,2020,24(20):11742-11754.

[37] CHEN S,LIU S,MA K,et al. TGF-β signaling in intervertebral disc health and disease[J]. Osteoarthritis Cartilage,2019,27(8):1109-1117.

[38] WONG J,SAMPSON S L,BELL-BRIONES H,et al. Nutrient supply and nucleus pulposus cell function: effects of the transport properties of the cartilage endplate and potential implications for intradiscal biologic therapy[J]. Osteoarthritis Cartilage,2019,27(6):956-964.

[39] HINGERT D,EKSTRÖM K,ALDRIDGE J,et al. Extracellular vesicles from human mesenchymal stem cells expedite chondrogenesis in 3D human degenerative disc cell cultures[J]. Stem Cell Res Ther,2020,11(1):323.

[40] 刘明强,陈海伟,张广智,等. 外泌体治疗椎间盘退变的研究进展[J]. 解放军医学杂志,2021,46(8):831-836.

(收稿日期:2022-06-06 本文编辑:吕宁)

(上接第55页)

[48] ATALAY H A,CANAT H L,ÜLKER V,et al. Impact of personalized three-dimensional-3D-printed pelvicalyceal system models on patient information in percutaneous nephrolithotripsy surgery: a pilot study[J]. Int Braz J Urol,2017,43(3):470-475.

[49] YANG L,SHANG X W,FAN J N,et al. Application of 3D printing in the surgical planning of trimalleolar fracture and doctor-patient communication[J/OL]. Biomed Res Int,2016,2016:2482086[2022-04-09]. https://pubmed.ncbi.nlm.nih.gov/27446944/.

[50] HORST A,MCDONALD F. Uncertain but not unregulated: medical product regulation in the light of three-dimensional printed medical products[J]. 3D Print Addit Manuf,2020,7(5):248-257.

(收稿日期:2022-04-10 本文编辑:郭毅曼)