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Current Applications of 3D Technologies in the Treatment of Bone Tissue Defects

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ABSTRACT

The use of 3D technologies offers more precise planning of surgical procedures in complex cases of localized bone tissue deficiency, allowing adaptation to individual anatomical features, improved outcomes, reduced risk of complications, and faster postoperative recovery. To analyze the current capabilities of three-dimensional printing in the surgical management of pelvic and hip bone defects, we reviewed scientific literature available in open-access databases including PubMed, eLibrary.Ru, Scopus, and Dimensions, with a search depth of up to 10 years. This review highlights major trends and advances in the medical application of 3D technologies aimed at reducing perioperative risks and improving patients' quality of life in the context of bone tissue defects. Particular focus is placed on revision hip arthroplasty and pelvic oncologic conditions, where modern additive manufacturing technologies can enhance treatment quality and surgical outcomes. The methodology of 3D scanning for designing patient-specific implants is described. The review also demonstrates current and promising applications of 3D printing in clinical practice. Modern 3D technologies, particularly additive manufacturing, play an important role in improving surgical outcomes for skeletal deficiencies by enabling personalized treatment, expediting recovery, and improving patient prognosis. Emerging directions significantly expand the range of available reconstructive procedures, reduce the risk of complications, and ultimately improve patient quality of life and surgical efficiency.

Keywords: bone tissue defects; revision hip arthroplasty; 3D technologies; 3D printing.

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Современные возможности применения 3D-технологий для лечения дефектов костной ткани

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АННОТАЦИЯ

Применение 3D-технологий позволяет достичь более точного планирования оперативных вмешательств в сложных случаях локального дефицита костной ткани, адаптировать их к анатомическим особенностям конкретного пациента, улучшая прогноз и снижая риск возможных осложнений, ускорить результаты восстановления пациентов в послеоперационном периоде. Для анализа информации о современных возможностях трёхмерной печати при оперативном лечении дефектов костной ткани таза, тазобедренного сустава мы использовали данные открытых электронных баз научной литературы PubMed, eLibrary.Ru, Scopus, Dimensions глубиной поиска до 10 лет. В обзоре рассмотрены основные тенденции и достижения в направлении использования 3D-технологий в медицине, способствующие снижению периоперационных рисков и улучшению качества жизни пациентов при дефектах костной ткани. Взгляд сфокусирован на проблеме ревизионного эндопротезирования тазобедренного сустава и онкологической патологии таза с возможностью применения современных аддитивных технологий с целью повышения качества лечения и результативности вмешательств. Описана методика 3D-сканирования для создания индивидуальных имплантатов. Продемонстрированы перспективы использования 3D-печати, актуальные способы применения аддитивных технологий в практической медицине. Современные 3D-технологии играют значительную роль в совершенствовании результатов хирургического вмешательства при дефиците костного скелета: аддитивные технологии позволяют индивидуализировать лечебный процесс, ускоряя выздоровление и улучшая прогноз пациента в будущем. Появляются перспективные направления, значительно расширяющие спектр проводимых реконструктивных операций, снижающие риски возникновения осложнений, что улучшает качество жизни пациентов и оптимизирует деятельность хирурга.

Ключевые слова: дефекты костной ткани; ревизионное эндопротезирование тазобедренного сустава; 3D-технологии; 3D-печать.

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BACKGROUND

Three-dimensional technologies are rapidly advancing, enabling the manufacture of patient-specific implants from various polymeric materials and facilitating the modeling of anatomical regions for improved visualization and preoperative planning. These capabilities contribute to reduced intraoperative risks, fewer complications, and shorter operative times [1]. The possibility of applying 3D printing (3DP) in medicine was first proposed in the 1980s when Chuck Hull was granted a patent in 1984 for a "Device for the production of three-dimensional objects by stereolithography" [2]. Since then, 3DP has evolved into a sophisticated robotic manufacturing method, driven by increasing demand, particularly in the field of biomedical engineering. The primary goal of 3DP is to fabricate precise models for performing complex and personalized procedures, such as organ reconstruction, targeted drug delivery, enhanced visualization, designing patient-specific dose-adjusted pharmaceuticals, producing 3D anatomical models for surgical planning and pathology analysis, manufacturing cost-effective surgical instruments, developing implants and devices for organ replacement, and life extension. [3]. Polymer-based 3DP is widely used to produce prostheses and implants, and living cells are used in bioprinting [1]. In orthopedic surgery, 3DP plays a significant role particularly in procedures involving the hip joint and pelvis [4]. Its four key clinical applications in this context include:

1) Fabrication of anatomical models for preoperative planning and surgical simulation
2) Production of patient-specific surgical instrument kits
3) 3D additive manufacturing of the prosthetic components
4) Direct 3D production of personalized prostheses [4, 5].

There is a growing need for total hip arthroplasty (THA), driven by the increasing incidence of pathologies affecting the hip, including new cases of coxarthrosis, femoral neck fractures, traumatic injuries, and their associated complications, such as avascular necrosis of the femoral head, autoimmune disorders, neoplasms, and metastatic lesions of the hip region [4]. When performed properly, THA can significantly enhance a patient's quality of life by reducing pain and restoring joint mobility [6, 7]. Primary THA has become a routine procedure for orthopedic trauma surgeons. However, its success depends on the surgeon's skill, clinical experience, and access to advanced technologies and equipment. Various innovative approaches have emerged to enhance procedural efficiency, minimize rehabilitation time, and lower the risk of complications [8]. These approaches are critical in optimizing THA outcomes [6]. Modern materials and technologies enable more accurate implant placement, low rates of complications, and improved functional outcomes. Complex cases of primary and revised THA require the use of auxiliary materials to reinforce the bone and fill the defects [9, 10].

DESCRIPTION OF 3D TECHNOLOGIES FOR PELVIC AND HIP ARTHROPLASTY

The Principle of 3D Scanning for Custom Implant Design

A key step in preparing a stable and biomechanically functional prosthesis is the preliminary scanning of the surgical region to assess defects and determine the most appropriate shape and optimal positioning of the prosthesis at the implantation site. Based on this information, osteointegration strategies and fixation methods are designed, taking into account the unique bone microarchitecture and the anatomical course of adjacent soft tissues and neurovascular bundles [11, 12]. Pelvic reconstruction typically relies on computed tomography (CT) imaging, with slice thicknesses ranging from 0.5 to 1 mm. Additional data on anatomical structures may be obtained through other imaging modalities, including ultrasound, radiography, and magnetic resonance imaging [13]. The 3D model may be built from two-dimensional images that are reconstructed by a biomedical engineer or, alternatively, derived from 3D CT data. The engineer removes the imaging noise and excludes soft tissues to produce a digital reconstruction of the target anatomy (e.g., the pelvis). In collaboration with an orthopedic surgeon, this digital model is refined to produce a full-scale (1:1) physical replica that reflects the patient's individual anatomy and defect morphology. Such a tangible model enables the surgeon to meticulously plan the procedure and optimize the positioning and fixation of the implant [1, 11]. The model creation process begins with converting the acquired imaging data into a digital format using specialized software that generates a 3D model based on the tomographic dataset. Alternatively, a prototype can be designed directly under Computer-Aided Design and CAM Computer-Aided Manufacturing environments without prior scanning. The software enables customization and optimization of the model and allows the user to detect and correct any structural defects or inconsistencies in the digital file [15]. Once the model fully meets the anatomical requirements, it is approved for printing and subsequent clinical use. Slicing is the transitional step between digital modeling and physical fabrication. During this stage, the 3D object is digitally divided into sequential layers, which are then reproduced by the printer head [14]. Rapid prototyping technologies, which build 3D objects layer-by-layer, are commonly used to produce patient-specific implants [15]. These technologies include stereolithography (SLA), selective laser sintering, and selective laser melting (SLM) [16]. Direct metal laser sintering (DMLS), a closely related technique, also uses metal powders to construct implant structures [17]. The construction process involves the sequential deposition and fusion of material layers according to the engineer-designed digital model. A laser beam sinters together powder particles and underlying layers, forming a solid structure under the control of an electromechanical mirror system. A key advantage of this method is its ability to create complex geometries, such as overhanging features, without requiring support structures. The finished product requires minimal mechanical finishing. The SLM technique also enables the fabrication of lattice structures, which enhance osteointegration and reduce stress shielding, thereby improving biomechanical compatibility with the patient's native bone [17].

Advantages of Using 3D Modeling in Surgical Planning

Surgical interventions in traumatology and orthopedics require meticulous planning, which increasingly involves the use of 3D technologies, not only for customizing prosthetic and implantable devices but also during preoperative preparation [14]. Traditionally, patient evaluation relied on instrumental imaging, but modern technologies enable the creation of personalized, physical 3D models of the target surgical area based on CT scans that replicate all individual anatomical features and defects and are used for planning surgical reconstruction [18, 19]. To generate an anatomically accurate model, patients typically undergo CT imaging of the pelvis and femur, with slice thickness typically ranging from 1.0 to 1.25 mm. The resulting imaging data are imported into specialized software for postradiologic processing and subsequent 3D modeling of the target area. The physical model is printed using polymer materials and accurately reflects all relevant anatomical details, including bone defects, particularly those of the acetabulum, which are often evaluated using the Paprosky classification [6]. The material used for the 3D model must meet the following criteria: lightweight, durable, flexible, impact-resistant, and mechanically stable. A personalized approach improves the anatomical fit of the implant, leading to a better joint function after surgery [20–22]. Apart from morphological variability and structural defects, orthopedic surgeons should also consider differences in biomechanical properties and bone mineral density, which influence the fixation method and long-term outcomes of THA [23]. 3D modeling of the anatomical region plays a vital role in selecting the most appropriate optimal implant. For bone graft viability, three essential biological properties are required: osteoinductivity, which induces the differentiation of progenitor (stem) cells into osteogenic lineages; osteoconductivity, which facilitates osteoblast proliferation and vascular ingrowth, resulting in osteoid formation; osteogenicity, which enables the graft material itself to integrate with the recipient's bone and maintain cell viability [23]. Virtual simulations allow for the testing of various implant configurations and positions within the joint, thereby increasing the likelihood of a successful outcome and reducing surgical time [24]. Preoperative preparation using a physical 3D model enables the surgeon to study the joint anatomy in greater detail and plan the procedure more thoroughly, which may reduce the operating time, minimize postoperative complications, and lower the risks of excessive bleeding and anesthetic burden [25]. However, some reports indicate that the use of such technologies may be associated with increased operative time and blood loss. As a result, it is recommended that the choice of treatment method be based on a well-reasoned, individualized decision-making process [26]. Enhanced precision in preoperative planning and intraoperative execution helps reduce postoperative risks and improve the overall effectiveness of surgery, highlighting the need for further research and clinical trials [27]. Because of improved accuracy, less invasive procedures, and faster postoperative recovery, patients are more likely to achieve favorable outcomes and regain a high quality of life [8].

Potential Benefits and Challenges of Using 3D Technologies in Bone Neoplasms

The application of 3D technologies is particularly relevant in pelvic and hip hemiarthroplasty after tumor resection [28]. Patient-specific implants, most commonly made of titanium, enable precise anatomical matching with the resected segment and facilitate faster rehabilitation in oncology patients who are often physically weakened [29]. Tumors in the pelvis and hip regions require technically demanding surgical procedures and an individualized approach as they are located in anatomically complex regions [30–33]. In oncology, every clinical case is inherently unique, not only in terms of disease progression and treatment strategies but also with respect to the patient's specific morphofunctional state, the surgeon's expertise, and the overall clinical course [34]. Additive manufacturing technologies help facilitate reconstructive procedures and should be used to tailor the treatment process to each patient to achieve better outcomes [35]. However, due to the limited awareness among healthcare professionals and patients regarding the capabilities and long-term outcomes of additive manufacturing in clinical practice, particularly in oncology, there is an ongoing debate about its safety and long-term efficacy, which hinders the clinical adoption of 3D-based treatment approaches [35, 36]. Thus, the integration of modern 3D technologies in pelvic hemiarthroplasty and THA is an important advancement in orthopedics, traumatology, and oncology. These technologies contribute to improved surgical outcomes and a better quality of life for patients. Unfortunately, many hospitals worldwide lack biomedical engineers to collaborate with orthopedic surgeons on 3D technology integration, leading to missed opportunities for implementing 3DP in clinical practice [37].

FORECASTS FOR THE DEVELOPMENT OF 3D TECHNOLOGIES IN MEDICINE

Trends and Innovations in 3D Technology

The demand for additive manufacturing technologies continues to grow rapidly each year, with an increasing number of medical specialties recognizing their potential and seeking to develop this field further [1]. The most active implementation of 3D innovations is seen in traumatology and orthopedics [8], neurosurgery [38, 39], dentistry [40], and medical education. In neurosurgery and dentistry, the need to perform highly complex surgical interventions with maximum efficiency and minimal postoperative complications motivates the use of additive manufacturing. Additionally, these procedures require the use of advanced, high-precision, and patient-specific implants [14].

Future Prospects for 3D Printing in the Development of Patient-Specific Implants

The growing demand for advancing additive technologies is driving the development of improved methods, materials, and printing systems [34]. For many years, research has been underway on using stem cells for the layer-by-layer bioprinting of organs for transplantation [42]. The main advantage of this approach is that it considers patient-specific anatomical features, which increases the chances of successful transplantation [41]. Apart from hardware improvements and the development of new printing technologies, there are efforts to modify the software that plays a key role in enabling the use of additive manufacturing [41]. These innovations include improvements in data acquisition on the modeled object, data analysis on the product and the patient's anatomy, integration of this information with the technological workflow, and algorithmic adaptation of the process to various levels of complexity. The transformation of the required specifications for the target object into a digital model is one of the essential stages in the design of an implant, prosthesis, or any other medical structure. This stage requires implementing cutting-edge technologies and the involvement of specialized experts [42].

CONCLUSION

In conclusion, modern 3D technologies play a significant role in improving surgical outcomes in patients with skeletal defects. The use of patient-specific anatomical 3D models enables surgeons to plan operations with a high degree of precision, leading to improved prognosis, reduced risk of complications, and better postoperative recovery. Successful integration of 3D technologies into clinical practice requires a close collaboration between biomedical engineers and surgical specialists. In the future, surgeons will operate using 3D navigation tools, while all surgical stages, including design and fabrication, will be automated. As 3D technologies continue to evolve, the range of available reconstructive procedures will expand significantly, ultimately improving the quality of life of patients who require such surgeries.

ADDITIONAL INFORMATION

Authors' contribution. B.S.V.—study concept and design, collection and processing of material, writing, editing; B.K.O.—study concept and design, collection and processing of material, writing; E.G.O.—study concept and design, collection and processing of material; P.I.A.—collection and processing of material, writing. Thereby, all authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.
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