Jurnal Eduhealth
Volume 15, Number 04, 2024, DOI 10.54209/eduhealth.v15i04
ESSN 2808-4608 (Online)
https://ejournal.seaninstitute.or.id/index.php/healt

Advancing Craniomaxillofacial Surgery: The Role Of 3D-Printing On Surgical Practices

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Article Info
Keywords:
3D-Printing
Craniomaxillofacial Surgery
Surgical Guides

ABSTRACT
Craniomaxillofacial (CMF) surgery is a specialized area of medicine that addresses a range of complex conditions affecting the skull, face, and jaw. These conditions can arise from congenital deformities, trauma, tumors, or diseases, and their treatment often involves highly intricate and technically demanding procedures. Traditional approaches to pre-surgical planning and treatment typically rely on 2D imaging and manual models, which can lead to increased time consumption, higher costs, and a greater likelihood of human error. Recently, the adoption of 3D printing technologies into CMF surgery has shown significant potential to improve both pre-operative planning and surgical outcomes. This article explores the transformative impact of 3D printing in CMF surgery, focusing on its application in creating patient-specific models that help optimize surgical precision. By utilizing detailed 3D scans (such as CT or MRI), These technologies allow the creation of highly precise, individualized physical models that replicate the anatomical structures of the patient. This level of precision helps minimize risks associated with surgery, such as the misalignment of bone structures or the inadvertent damage to critical tissues. Emulating the surgical process on a 3D-printed model allows surgeons to enhance their techniques and predict potential challenges, ultimately improving surgical outcomes. Nonetheless, the integration of 3D printing in CMF surgery presents certain challenges. High production costs, the need for specialized equipment, and a lack of standardized protocols pose barriers to widespread adoption. Moreover, regulatory and legal issues need to be addressed to ensure patient safety and adherence to medical standards. In conclusion, 3D printing represents a groundbreaking advancement in CMF surgery, offering substantial improvements in surgical accuracy, patient care, and recovery outcomes. As the territory of 3D printing develops, it stands to greatly improve craniomaxillofacial surgery through safer, more efficient, and personalized solutions.

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INTRODUCTION

Originally created for industrial use, 3D printing has quickly transformed into a game-changing technology in the medical industry. This technology has been used to solve a number of medical issues since it was first developed in the 1980s, most notably in surgical procedures involving intricate anatomical systems (Whitaker, 2014). Custom implants and surgical planning models were among the first medical applications, especially when traditional methods proved insufficiently precise and flexible (Parthasarathy, 2014; Robiony et al., 2007). Since it allows for accurate preoperative planning and solutions that are designed specifically for patient needs, 3D printing has turned up as an indispensable asset in enhancing medical outcomes.

In the realm of surgery, the utility of 3D printing is most pronounced in craniomaxillofacial procedures, which involve some of the most intricate structures of the human body. This region encompasses a variety of challenges arising from congenital deformities, traumatic injuries, infections, and oncological conditions (Greenberg & Schmelzeisen, 2019). Among these, trauma remains the most prevalent cause, with fractures of the craniofacial region commonly observed in young adults aged 21–30 years, predominantly males (de Lucena et al., 2016). Urban settings, characterized by higher population density and increased vehicular activity, report a significantly higher incidence of such injuries compared to rural areas (Rocha et al., 2024). Addressing these complex pathologies demands meticulous surgical planning and execution, where 3D printing has become a transformative technology with significant implications.

The facial skeleton's complexity often requires tailored surgical approaches to ensure optimal functional and aesthetic restoration. Historically, surgeons relied on generalized templates and approximations, which frequently resulted in suboptimal outcomes, such as prolonged recovery times or residual deformities (Rocha et al., 2024). The integration of 3D printing into surgical workflows has revolutionized this process by enabling the development of accurate, patient-customized models for enhanced surgical planning and outcomes based on several radiology imaging such as CT Scan and MRI. These models are invaluable for planning surgeries, intraoperative guidance, and even as prosthetic implants (Ostaș et al., 2022). By improving surgical precision and reducing intraoperative errors, this technology enhances both the efficiency of procedures and patient outcomes.

The modern uses of 3D printing in craniomaxillofacial surgery are explored in this article. It discusses the drawbacks and difficulties of incorporating it into therapeutic practice, looks at noteworthy case cases, and investigates its many advantages. This essay aims to highlight the revolutionary potential of 3D printing in redefining standards of care in this specialist surgical sector by offering a thorough review.

METHODS

This study employs a qualitative approach with a case study design to analyze the application of 3D printing technology in cranio-maxillofacial surgical procedures. The main objective of this research is to identify the benefits, challenges, and impacts of using 3D printing technology in enhancing the accuracy and outcomes of various surgical procedures, particularly in the fields of reconstructive surgery, oncology surgery, and the treatment of congenital abnormalities. The research is conducted in several hospitals that have integrated 3D printing technology into their surgical practices. The research subjects consist of medical professionals, including surgeons, 3D printing technicians, and nurses involved in surgical procedures using this technology, as well as patients who have undergone cranio-maxillofacial surgery with the aid of 3D printing.

For data collection, this study uses three main techniques: in-depth interviews, participatory observation, and documentation. Interviews are conducted with medical professionals and patients to explore their views and experiences regarding the application of 3D printing in surgical procedures. The interview questions focus on perceived benefits, challenges faced, and practical experiences with the use of this technology. Participatory observation is conducted by the researcher participating in surgical procedures utilizing 3D printing technology to directly observe its implementation in clinical practice. Additionally, documentation in the form of analysis of medical records and reports of surgical procedure outcomes is used to complement the research data. The data obtained is then analyzed using a thematic analysis approach to identify key themes related to the application of 3D printing, such as efficiency, accuracy, technical challenges, and the impact on surgical outcomes. To maintain the validity and reliability of the data, this study adopts data triangulation by combining interviews, observations, and documentation as primary sources. Furthermore, member checking is also applied to verify the preliminary findings obtained from the informants.

RESULTS AND DISCUSSION

Application Of 3D-Printing In Craniomaxillofacial Surgical Procedures

One significant uses of 3D printing is in creating models or guides that allow surgeons to use either preoperative or intraoperative (Slavin et al., 2023). Surgeons are able to visualize and go over the procedure with better precision than traditional methods, which often depend on generalized approximations (Slavin et al., 2023). The utilization of 3D printing extends to creating customs implants and graft specifically modified to each patient's needs (Slavin et al., 2023). For example, in craniomaxillofacial surgery, implants can be created to with highly intricate geometries and porous structures to help promote osseointegration, which is an important factor in the outcome of reconstructive surgeries (Lin & Yarholar, 2020) 4 types of products are used in surgery procedures (Lin & Yarholar, 2020): Type I – Patient-Specific Anatomical Models, type II – Custom Surgical Guides, type III – Patient-Specific Implants (PSI), type IV – Bio-Printed Tissue and Organ (Lin & Yarholar, 2020). Anatomical models are the most widely used in surgery, it is often the replicas of the patient (Burde et al., 2021). Derived from advanced imaging techniques like CT and MRI scans, it helps visualize deformities, fractures, and neoplasms (Burde et al., 2021). These help surgeons assess the exact dimensions and spatial relations of the bones and surrounding tissues, lowering surgical uncertainties (Burde et al., 2021).

Surgical guides are designed to improve the accuracy of procedures by assisting positioning and orientation of surgical instruments (Wang et al., 2024). Customized to each patient's anatomy and procedure plan, it ensures the procedure such as bone cutting, drilling, or placement of the implant can be accurately executed (Wang et al., 2024). These guides are very valuable especially in orthognathic surgeries following trauma or cancer removal.[12]

Furthermore, using guides also reduce surgery time and therefore reduce patient's exposure to anesthesia (Wang et al., 2024).

Anatomical Models

Anatomical models, which provide accurate, patient-specific representations of anatomical structures, are among the most popular 3D printing uses in surgery These models, which are derived from sophisticated imaging methods like CT and MRI scans, give surgeons the ability to preoperatively plan surgeries with a level of detail that is not possible with conventional imaging For instance, these models enable accurate imaging of deformities, fractures, or tumor placements in delicate bone structures required in complex craniomaxillofacial procedures (Meng et al., 2019). They lower surgical uncertainty by assisting surgeons with determining the precise measurements and spatial relationships of bones and surrounding tissues (Ghai et al., 2018). Because any difficulties can be foreseen and minimized before the actual surgery, preoperative planning reduces operating time and improves patient safety (Ghai et al., 2018). In trauma situations requiring intricate adjustment of cranial or facial fractures, printed models have proven especially helpful (Chytas et al., 2020; Ghai et al., 2018) Surgeons can better comprehend the patient's unique anatomy by practicing the procedure beforehand with a realistic, life-sized model of the damaged area (Ghai et al., 2018). For trainees and residents who learn best through tactile and visual means, this is quite beneficial. Because surgeons are better prepared, studies indicate that using these models can cut down on surgery time by up to 20% (Ravi et al., 2023).

Surgical Guides

Another essential 3D-printed equipment is the surgical guide, which helps with the orientation and positioning of surgical instruments to increase surgical procedure precision (Zeid et al., 2024). These guides guarantee that operations like bone cutting, drilling, or implant insertion are carried out exactly as they are customized to align with the patient's anatomy and surgical requirements (Steinbacher, 2015). Because millimeters can make or break an operation, this accuracy is especially crucial in craniomaxillofacial surgery (Steinbacher, 2015; Zeid et al., 2024) Surgical guides are usually sanitized and printed using biocompatible materials before being used in the operating room (Zeid et al., 2024). These guidelines are particularly helpful for reconstructive procedures after trauma or cancer excision, as well as orthognathic surgeries (jaw surgeries) (Hadad et al., 2023). According to one study, using 3D-printed surgical guides during mandibular restoration greatly enhanced bone graft alignment, reducing the risk of malocclusion and other post-operative problems (Hadad et al., 2023; Wang et al., 2024). Moreover, surgical guides streamline procedures, cutting down on the time spent on surgery and the amount of anesthesia that patients must endure (Hadad et al., 2023).

Custom Implants

Custom implants created to suit a patient's specific anatomical features represent one of the most transformative uses of 3D technology in medical procedures (Costanzo et al., 2022). Conventional implants, which are frequently produced in uniform sizes and forms, are not always able to meet each person's specific anatomical features and structural requirements (Costanzo et al., 2022). On the other hand, 3D printing makes it possible to create highly tailored implants that closely match the patient's bone structure, offering better results in terms of fit, functionality, and appearance (Kim et al., 2020). Custom implants are especially useful in craniomaxillofacial surgery, where facial symmetry and function are crucial (Thieringer et al., 2018). These implants are made to blend in perfectly with natural bone and can be made of titanium, polyetheretherketone (PEEK), or biocompatible polymers (Murr, 2020). For example, bespoke implants can more accurately replace bone lost due to disease or damage than standard transplants in situations of face trauma or post-oncology treatment (Murr, 2020; Thieringer et al., 2018). Furthermore, osseointegration—the physical and functional integration between bone tissue and the implant—is promoted by the porosity aspect of certain 3D-printed implants (Kia et al., 2022). Globally, craniomaxillofacial procedures employ patient-specific implants made by Materialize, a pioneer in 3D printing for healthcare(Jindal et al., 2021). These implants provide better functional results, especially when big flaws are involved, when conventional methods frequently fail (Zeid et al., 2024).

Bio-printed Tissue Scaffolds

Bioprinting, a form of 3D printing in surgery, is still in its infancy but has the potential to completely transform organ transplantation and tissue regeneration (Dwivedi & Mehrotra, 2020). In order to produce tissue scaffolds that aid in the regeneration of native tissues, biomaterials are layered, frequently in conjunction with living cells (Shin et al., 2021). Bio-printed scaffolds are being investigated for their potential to replace lost bone, cartilage, and soft tissues in craniomaxillofacial surgery as a result of accident, illness, or birth defects (Dwivedi & Mehrotra, 2020; Shin et al., 2021). In reconstructive procedures where autologous tissue grafts are either insufficient or unavailable, the idea of bioprinting is very alluring (Dwivedi & Mehrotra, 2020; Shin et al., 2021). The architecture of bio-printed scaffolds is similar to that of real tissues, and they can be made to break down gradually while the patient's own cells grow on them and produce new tissue (Dwivedi & Mehrotra, 2020). Initial studies have shown potential in animal experiments and limited human trials, but widespread clinical implementation is still under development (Wu et al., 2020).

Clinical Applications of 3D-printing in Craniomaxillofacial Surgery

Reconstructive Surgery

Reconstructive surgery now relies heavily on 3D printing, especially when treating trauma-related craniomaxillofacial lesions (J. W. Choi & Kim, 2015; Matias et al., 2017). These consist of zygomatic complex fractures, mandibular disruptions, and orbital wall fractures (J. W. Choi & Kim, 2015). Preoperative planning with unparalleled precision is made possible by patient-specific models created from CT and MRI scans, which lower surgical risks and enhance results (J. W. Choi & Kim, 2015).

One such instance had a patient who received treatment in Singapore after suffering a serious mandibular deformity in a car accident (J. W. Choi & Kim, 2015). To repair the flaw, surgeons used a titanium plate that was 3D printed (Y. W. Choi et al., 2019; Matias et al., 2017). The customized design of the implant guaranteed ideal bone alignment and sped up the healing process (Matias et al., 2017). The application of patient-specific implants (PSIs) for orbital reconstruction was highlighted in another case that was published from a Korean

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center (Kang et al., 2022). With a success rate of over 90%, these implants restored facial symmetry, demonstrating the revolutionary potential of 3D printing (Matias et al., 2017).

Cancer Surgery

In oncology, substantial abnormalities necessitating intricate repairs are frequently left behind after surgically excising malignancies in the craniomaxillofacial area (Y. W. Choi et al., 2019; Matias et al., 2017). This is supported by 3D printing, which enables precise excision and reconstruction by creating customized surgical guides and implants tailored to the patient's anatomy (Matias et al., 2017). This method reduced the loss of healthy tissue while simultaneously increasing surgical accuracy, improving both the cosmetic and functional results (Y. W. Choi et al., 2019). Furthermore, 3D-printed bioengineered scaffolds are being used into post-resection treatments (Kang et al., 2022).

Congenital Deformities

3D printing has greatly improved the ability to correct congenital abnormalities such hemifacial microsomia, craniosynostosis, and cleft palate (J. W. Choi & Kim, 2015; Lopez et al., 2018). Surgeons can foresee difficulties, optimize outcomes, and simulate the procedure using preoperative models (Lopez et al., 2018) This resulted in better postoperative results and a 20% decrease in operating time. Hemifacial microsomia has also been reported to be treated using custom implants (Liu et al., 2024; Lopez et al., 2018). A joint project in Japan created an implant for a young kid using 3D printing, resulting in a restoration that was both aesthetically pleasing and functional (Kodama et al., 2008).

Trauma and Emergency Applications

In emergency situations, 3D printing is a perfect choice because traumatic injuries frequently require quick yet accurate interventions (Bergeron et al., 2021; J. W. Choi & Kim, 2015). The usage of 3D-printed surgical guides in the reconstruction of various cases of badly damaged face was demonstrated by a Canadian institution (Bergeron et al., 2021). The patient-specific guidance enhanced fracture alignment and cut operating time by more than 30%.

Advancement in Material Science

Developments in materials are also essential to the success of 3D printing in craniomaxillofacial surgery (Bergeron et al., 2021) Because of their compatibility and mechanical qualities, biocompatible polymers like polyetheretherketone (PEEK) are being utilized more and more for PSIs (Bergeron et al., 2021) Polylactic acid (PLA) is one of the emerging bioresorbable polymers being investigated for pediatric situations to reduce the need for additional procedures as the kid grows (Bergeron et al., 2021).

Advantages And Setbacks

Craniomaxillofacial surgery has experienced a transformative shift with the adoption of 3D printing technology, which has brought forth both unique challenges and important advantages (Tejo-Otero et al., 2020). This section examines both aspects to thoroughly assess the technology's impact. The most evident advantage is the increase in surgical accuracy. Surgeons might use patient-specific anatomical models made from CT or MRI to practice challenging procedures and anticipate challenges. Preoperative planning significantly reduces intraoperative errors, speeds up surgery, and improves outcomes (Tejo-

Otero et al., 2020). For example, it has been shown that using 3D models during congenital abnormality repair surgery increases precision and yields superior functional and cosmetic results (Tejo-Otero et al., 2020). Another benefit is that implants and grafts can be customized. Traditional implants sometimes require intraoperative modifications, which lengthens operations and increases risks (Tejo-Otero et al., 2020). Conversely, 3D-printed implants are already manufactured to exactly fit the anatomy of the patient. This customization not only improves surgical outcomes but also expedites recovery because of improved osseointegration (Tejo-Otero et al., 2020).

Another significant benefit is the potential to incorporate cutting-edge biomaterials into the printing process (Tejo-Otero et al., 2020). Bioactive composites (Dukle et al., 2022; Tejo-Otero et al., 2020) titanium (Abar et al., 2022) and polyether ether ketone (PEEK) (J. Kang et al., 2021; Kennedy et al., 2024) are materials that replicate the biomechanical characteristics of soft tissues and bone. These materials lower rejection rates while improving compatibility and durability (Kennedy et al., 2024). In oncological reconstructions, when obtaining both form and function is crucial, this is especially important. Another important advantage is cost effectiveness (Rooney et al., 2020; Wong et al., 2022). By reducing operating hours and avoiding problems, 3D printing lowers the overall costs of procedures, despite the expensive initial setup costs (Ballard et al., 2020). Furthermore, the capacity to locally create low-cost implants and prostheses is revolutionary in low-resource settings, increasing access to cutting-edge surgical care (Ballard et al., 2020).

Despite these benefits, a number of obstacles prevent broad adoption. The regulatory environment surrounding medical equipment that are 3D printed is still complicated (Kumar Gupta et al., 2022). Standardized procedures for guaranteeing the effectiveness and safety of these devices are lacking. Guidelines have been set by regulatory agencies like the FDA, but adherence varies worldwide, which delays clinical implementation (Beitler et al., 2022). Significant challenges are also presented by material constraints (Tian et al., 2021). Despite their widespread use, metals like titanium have limited applications because to their high cost and lack of biodegradable alternatives (Tian et al., 2021). Additionally, it is challenging to achieve uniformity in mechanical qualities throughout the printing process, which results in variations in final quality.

The lengthy nature of the design and printing procedures is another important problem. 3D printing is useful for scheduled procedures, but it is less useful in emergency scenarios where prompt action is needed, such acute trauma cases. Additionally, ethical issues come up, especially when handling private patient data that is utilized to build models (Tejo-Otero et al., 2020). Getting informed permission and protecting data are important but frequently disregarded factors (Tejo-Otero et al., 2020). Additionally, smaller institutions have challenges due to the high initial expenditures of 3D printing technologies, particularly in underdeveloped nations (Serrano et al., 2020). Finally, there is a significant learning curve involved in implementing 3D printing (Frendø et al., 2021). Surgeons need multidisciplinary training because they must work with engineers and technicians (Frendø et al., 2021) This reliance on specialist knowledge may cause delays in healthcare settings (Frendø et al., 2021)

CONCLUSION

The application of 3D printing in craniomaxillofacial surgery has significantly improved surgical precision and outcomes. This technology enables the creation of patient-specific anatomical models, surgical guides, custom implants, and bio-printed tissue scaffolds. These innovations help surgeons plan and execute procedures with greater accuracy, reducing surgical time and improving recovery. Patient-specific anatomical models, derived from CT and MRI scans, allow surgeons to visualize deformities, fractures, and tumors in detail, enhancing preoperative planning. Surgical guides further increase accuracy in procedures like bone cutting or implant placement, particularly in trauma or oncology cases. Custom implants tailored to each patient's anatomy provide better fit and functionality, promoting osseointegration and faster recovery. Bio-printed tissue scaffolds, still in early stages, offer promising potential for tissue regeneration in cases where autologous grafts are unavailable. Clinical applications include reconstructive surgery, cancer surgery, treatment of congenital deformities, and emergency trauma cases, with 3D printing offering significant benefits such as reduced surgery time and improved functional and cosmetic results. Despite these advancements, challenges remain, including regulatory issues, material limitations, and high initial costs. Additionally, the long design and printing processes may limit the use of 3D printing in emergency situations. Ethical concerns regarding patient data and the need for specialized training for surgeons further complicate widespread adoption. Nonetheless, the potential of 3D printing to revolutionize craniomaxillofacial surgery is clear, offering more precise, cost-effective, and personalized treatments.

ACKNOWLEDGEMENT

The author would like to express sincere gratitude to Lau Simomo General Hospital for Leprosy for their support and the opportunity provided in conducting this research. Special thanks also go to all parties involved for their invaluable assistance and cooperation. May this collaboration be beneficial for the development of knowledge in the field of health.

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Jurnal Eduhealth
Volume 15, Number 04, 2024, DOI 10.54209/eduhealth.v15i04
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