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Transforming Implantology: The Role of 3D-Printed Guides in Advancing Standards of Care (2017-2024)

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ABSTRACT

This study focuses on the effects of 3D-printed surgical guides on the accuracy and reduction of errors among novice surgeons in maxillofacial surgery. The effectiveness of these guides in practical surgical settings was evaluated through an action research and field research design with a descriptive content analysis of a compilation of qualitative data and interviews. The results demonstrate a notable reduction in surgical errors, enhancement in surgical outcomes, shortening operating time, and an educational benefit for novice surgeons. The results indicate that 3D-printed guides are effective in improving surgical precision and may reduce malpractice insurance costs. This study emphasizes the capability of personalized medical devices to enhance outcomes for both patients and practitioners.

Introduction

Setting the stage for the impression, the smile receives the first glance. The maxilla's stillness balances with the mandible's motion, cloning together to project the image of the rows of teeth pertinent to each person. Yet, through age, lack of care, disease, and other factors, tooth decay could deprive people of functionality and physical appearance. Titanium dental implants offer a practical and appealing option for patients to regain dental functionality and confidence in their smile, differing from a bridge or removable denture that lacks mechanical function. Years after Swedish scientist Branemark developed dental implant surgery (Guillaume, 2016), freehand surgery adopted technologies such as Cone-Beam Tomography Scanning and Static or Dynamic surgical approaches to increase the precision of implant placement. As three-dimensional printing emerged in the medical field, dental implantology followed these advancements, introducing 3D-printed surgical guides to lead surgeons through a fast, more cost-effective, precise, and personalized approach to the procedure.

3D printing and virtual surgical planning have significantly increased prominence within oral and maxillofacial surgery, enhancing precision and personalization for implant operations. This study evaluates the influence of surgical guides on the precision, educational distinction, and cost-efficiency of dental implantation, emphasizing the learning curve for novice surgeons and the individualized advantages they offer to patients. Rooted in a review of current literature and fieldwork with experts such as Dr. Rafael Gavilanes, the study examines how surgical guidelines facilitate implant placement, decrease procedural variability, and alleviate prevalent surgical problems via standardized, individualized planning, thereby improving surgical outcomes and patient satisfaction.

By emphasizing the teaching value of 3D printing, this study assesses surgical instructions' role in aiding new practitioners to make fewer mistakes. 3D-printed models allow students to safely practice intricate operations, cultivating vital skills without jeopardizing patient safety. Beyond surgical preparation, 3D printing surgical implant guides revolutionized dental implantation. Evidence indicates that inexperienced operators acquire higher levels of precision with guided instruments than expert surgeons executing freehand procedures. This study seeks to provide a comprehensive knowledge of guided implantology's influence on the future of oral and maxillofacial surgery, focusing on the advancing role of technology in medical education and practice. It emphasizes precision and individualized treatment, highlighting technology's transformational capacity to overhaul traditional standards of care.

Extensive research highlights the importance of harmonizing standardization with personalized care, exemplified by Ansmann and Pfaff's idea of "individualized standardization," which focuses on tailoring treatment within standardized procedures to meet each patient's unique specifications. Integrating 3D printing in maxillofacial surgery addresses customization consistently, providing surgeons with precise, patient-specific guidelines that improve surgical precision. The comprehensive procedures in guided implantology - encompassing data acquisition, virtual implant design, and guide fabrication - provide a reliable surgical workflow. The research examined by Dioguardi et al. and Jwa-Young et al. indicates that these guides enhance precision, expedite post-operative recovery, and enhance patient satisfaction.

Problem Statement

The application of 3D surgical implant guides in dental procedures aims to enhance the accuracy and precision of implant placements compared to conventional free-hand methods. However, when the 118th Congress passed the Medicaid Dental Benefits Act of 2023 for states to expand their Medicaid programs to ensure dental and oral health services, the Centers for Medicare and Medicaid Service was left responsible for establishing “oral health quality and equity measures.” While insurers such as Humana, Triple-S, and AARP (surprisingly not Medicare) cover dental implants, patients are often limited to maximum coverage and especially do not include any additional costs for the surgical guide. This investigation brings awareness to the correlation between the conventional standard of care established (free-hand implants) and the need for insurance coverage. Through the modifications of the standard of care for implantology, insurance coverage could extend to include the costs tied to the surgical implant guide under the costs of dental implants.

Purpose

This study aims to evaluate the effects of 3D-printed surgical guides on accuracy, efficiency, and skill development in oral and maxillofacial implantology, intending to recommend improvements to the existing standard of care. This study examines the effectiveness of both experienced and novice surgeons using surgical guides, emphasizing the guides' role in reducing human error, improving implant accuracy, and supporting the educational growth of inexperienced practitioners. Furthermore, it analyzes the integration of technology in harmonizing standardization with personalized patient care, facilitating customized therapies that account for anatomical differences. This study emphasizes the necessity of incorporating surgical guidelines into standard practice to provide consistent, high-quality outcomes and enhance patient satisfaction based on fieldwork with maxillofacial surgeons and an extensive literature review. The investigation aims to identify optimal practices within the industry, promoting the adoption of 3D-printed guides as a standard tool to enhance training and elevate patient-centered care.

Justification

This study examines the increasing need for accuracy, efficacy, and customization in oral and maxillofacial implantology. The use of 3D-printed surgical guides provides surgeons with instruments that facilitate precise, customized treatments, minimizing human error and addressing anatomical complexities. This device significantly improves patient outcomes by assuring accurate implant placement. It establishes a new benchmark in surgical education, allowing rookie surgeons to practice accurately and confidently early in their careers. Distinctiveness in this investigation lies in examining how 3D-printed guides may transform the standard of care, transitioning implantology from free-hand techniques to a systematic, guided methodology. This research demonstrates the beneficial impact of these aids on surgical results and training, enhancing the comprehension of how technology might reconcile uniformity and individualization in medicine. Informing practitioners and the public about these advantages may encourage the broader implementation of guided implantology, enhancing global standards of care and patient satisfaction.

Research Questions

1. In what ways does the utilization of 3D printing technology enable the development of surgical implant guides with standardized personalization?
2. What are the possible effects of utilizing 3D-printed surgical implant guides on minimizing mistake rates in maxillofacial procedures, and how does it impact the outcome for novice maxillofacial surgeons?
3. In what ways does the use of 3D printing technology in maxillofacial surgery disrupt or transform existing standards of care, and what consequences does this entail for preventive medicine and medical malpractice insurance?

Research Objectives

1. To evaluate the impact of 3D-printed surgical guides on implant precision, procedural efficiency, and surgeon training outcomes in maxillofacial implantology.
2. To propose modifications to current standards of care in implantology by integrating 3D-printed surgical guides, balancing personalized patient care with procedural standardization.
3. To analyze the role of 3D-printed surgical guides in reducing procedural variability and minimizing surgical complications in maxillofacial implantology.

Theoretical Framework

The utilization of 3D-printed surgical guides in maxillofacial implantology represents a critical shift toward patient-centricity and precision, surpassing the limitations of traditional free-hand techniques. The concept of "individualized standardization," as defined by Ansmann and Pfaff (2017), underscores the importance of personalized surgical techniques within standardized protocols. This equilibrium is achieved by surgical guides, which customize each guide to the patient's unique anatomy. Research suggests that 3D printing enables precision preoperative planning, improving surgical predictability and patient satisfaction (Jwa-Young et al., 2023). By providing exhaustive roadmaps for implant placement, these instructions alleviate the unpredictability and issues inherent in previous methods (Dioguardi et al., 2023).

Furthermore, using 3D-printed guides has improved surgical training by enabling novices to acquire practical experience with complex operations securely (Pugliese & Marconi, 2018). Based on the evidence presented by Firas et al. (2019), digital-guided implant surgery enhances accuracy by reducing angle, depth, and lateral variations compared to free-hand approaches. The research emphasizes the transformative potential of surgical guides in implantology, which can improve outcomes and establish a new standard of care.

Definition of Terminologies

1. Angular Deviation: In the context of implantology, angular deviation refers to the difference between the planned and actual angulation of an implant's placement. It measures the extent to which the implant's angle deviates from the preoperative plan, affecting the implant's alignment and potentially impacting long-term stability and function. Accurately managing angular deviation is crucial for successful osseointegration and aesthetic outcomes.

2. Axial: Axial refers to an orientation along or parallel to the long axis of the implant or tooth (Figure B in Appendix).
3. Apical: Apical pertains to the apex, or tip, of the implant (analogous to the root tip in a natural tooth) (Figure B in Appendix).
4. Sleeves of the Implant: Sleeves are cylindrical guides or inserts within surgical guides that help position the drill and implant accurately. They control the direction, angle, and depth of drilling, enhancing precision by guiding the tools according to the preoperative plan. Sleeves are typically custom-designed to fit the specific implant size and surgical guide, and their accuracy is crucial for reducing deviation and achieving predictable implant placement (Figure A in Appendix)
5. Implantology: The term "implantology" refers to the branch of dentistry and oral surgery focused on the placement and maintenance of dental implants (Figure C in Appendix).
6. Osseointegration: Coined by Per-Ingvar Brånemark in the 1950s, "osseointegration" describes the direct structural and functional connection between living bone and the surface of a load-bearing implant, usually titanium (Figure B in Appendix).
7. Surgical Guide: The concept of a "surgical guide" emerged alongside advancements in medical imaging and 3D modeling in the late 20th century, referring to a device used to position surgical instruments or implants accurately. In dental implantology, surgical guides became widely recognized in the 1990s, with the integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies (Figure A in Appendix).

Review of Literature

Individualized Standardization as a Solution

Amid the rapidly evolving field of implantology, individualized standardization emerges as a groundbreaking solution, bridging the precision of personalized care with the efficiency of standardized protocols to redefine the future of dental procedures (OpenAI, 2024).The article highlights the competing principles of standardization and individualization within the healthcare system, pointing out the limitations imposed by standardization. Proposing a solution in the form of "individualized standardization," the article calls for training doctors to balance the opposing ideas. The commentary emphasizes that although standardization through clinical guidelines ensures consistency in diagnosis, the need for individualizing patient care and diagnosis increased as an outcome of new personalized medicine and dual diagnostics – multiple illnesses simultaneously affecting the patient. The author combined the definitions of customization (adapting treatment to the patient's psychological, social, and cultural aspects) and personalization (adjusting treatment based on the patient's biological characteristics) of patient needs under the term individualization: the "tailoring of healthcare to the specific biological, psychological, social, and cultural needs of the patients." By contemplating the preservation of social systems, the article urges healthcare workers to implement standardized individualization by adapting guidelines to frameworks flexible enough to accommodate the patient's needs; hence, increasing patient care as patient treatment and diagnosis are viewed as a representation of an individual case, not as something that can be limited to established criteria. An example of the efficiency of "standardized individualization" is the multidisciplinary team meetings, composed of oncologists, radiologists, pathologists, and other specialties, formed to discuss diagnosis, prognosis, and treatment plans for patients with cancer. Although standardization presents itself as evidence-based protocols and guidelines are abided by, policies in the treatment are furnished to the social environment, psychological state, and patient preference. This source explains the following:

Individualization, as described above, means taking into account the biological, psychological, social and cultural dimensions of the patient, eg, patient preferences and wishes. The theoretical background is the concept of context management according to systems theory. "Context management can be viewed as a technique that creates an environment in which an autopoietic target group is more sensitive to steering signals. Context management is a technique making use of the self-referential closure of the autopoetic target group."17 Transferred to healthcare, Context management creates an environment in which the patient-physician interaction is sensitive to steering signals, eg, guideline knowledge, quality management activities, expertise from other disciplines and molecular diagnostics. Within this context treatment has to be individualized within a given framework (ie, standardization). The aim is to merge evidence with patient preferences. (Ansmann & Pfaff, 2017)

Although the focus of this investigation veers toward the applications of 3D printing, virtual surgical planning, and surgical guides, this source provides insight into the necessity for patient-individualized diagnosis, prognosis, and treatment. Implementing this new technology is crucial to achieving personalized care and, more importantly, patient-personalized surgeries. Although the source focuses on general recovery treatment from illness diagnosis, the same principles should be applied to orthognathic and oral maxillofacial surgery. The principles outlined in the source for general recovery treatment from illness diagnosis should also be applied to orthognathic and oral maxillofacial surgery. A patient's biological, social, psychological, and cultural aspects must all be accounted for within the surgical planning and post-operative treatment, as it is integral for diminishing complications due to unpredictability prominent to the usage of standardized models, inaccurate cadavers, and generalized guidelines for surgery. Through 3D models of the person's oral anatomy, the surgeon can predict complications more accurately and form more efficient solutions tailored to solve the problems specific to the patient's case. The commentary supporting the implementation of standardized yet personalized patient care regarding this investigation justifies the essentiality of implementing technology to reach new goals in changing the nature of standardized care within the healthcare system. While focalized on proposing a change in the standard of care for implantology in oral maxillofacial surgery, this investigation seeks to spotlight the role of surgical guides, a three-dimensional advancement, to reach the goal of transitioning from free-hand implantation to guided surgery for complex cases. Technology has been at the forefront of the evolution of man in every evolutionary stage; hence, its implementation through surgical guides and 3D-printed models is essential for accomplishing this emerging goal in medicine.

Dental Implants: A Review

Evolving from the efforts to improve dental functionality, dental implants provide a different solution from removable dentures or bridges, all of which are supported by fixed teeth susceptible to quicker decay due to the excess dependence placed on them. For this reason, the dental implant screw - made from titanium - mimicked the tooth's root as it integrated into the mandible bones, also known as the process of osseointegration. After an ample period granted for the full completion of the integration of the screw to the bone, dentists are tasked to load the implant with a prosthesis. However, other authors propose the process of immediate loading, where the implant is loaded with a temporary prosthesis immediately after placing the screw. Consequences emerge from this procedure, as the exposure to chewing force may delay osseointegration due to excessive stress placed onto the bone, in addition to the stress of accepting the titanium screw. However, the overall procedure for implant placement, involving the patient under local or general anesthesia (most commonly local), is as follows : (1) grade II American Society for Testing and Materials threaded implants are administered for the surgery, (2) drilling low-speed with irrigation to prevent deterioration of osteocytes and osteoblasts (osseous cells), incrementing the size of the drill until the width of the implant is achieved, (3) locking fixture after screwing, (4) suture of the gingival tissue above implant (if flap surgery, if flawless, does not apply), and (5) placement of prosthesis of the implant after six months (if immediate loading, this does not apply, as the gingival mask is not torn before implant placement). Through follow-up X-rays, surgeons must identify peri-implantitis or inflammation at the site of the implant mobility, usually appearing as a radiolucent (white) edging around the implant. If present, the implant must be removed entirely to control the damage made to the bone. Contraindications (factors denying the option for implantation) include patients receiving intravenous amino-bisphosphonates for hematologic malignant diseases due to the probability of osteonecrosis of the jaw. When the treatment is administered for patients with osteoporosis, the patient can be considered for the implant, yet it is guaranteed. Smoking, massive bone loss, occlusion disorders (alignment of the lower and upper jaw), and poor oral hygiene are considered local contraindications or factors that increase the risk of failure. The source lists the steps involved in placing an implant as the following:

The clinical success of the method was based on the following points: the use of grade Il ASTM titanium (American Society for Testing and Materials) threaded implants adapted to the patient's specific anatomy; a drilling at low speed and an implementation of the fixture under irrigation to avoid a thermal rise which is particularly harmful to osteocytes and osteoblasts and deleterious to osseo-integration; locking the fixture at the end of screwing (so-called 'primary locking'). It is estimated that locking is obtained for a torque of 20-30 N; suture of the gingival tissue above the implant at the end of the surgical procedure; placement of the prosthesis on the implant after a 6-month period to ensure that it is firmly attached to the bone whose texture is lamellar with a high biomechanical competence at the tissue level. The relevance of this surgical process and the nature of the biomaterial used were rapidly adopted by the dental and stomatology communities due to long-term success rates. For the first time, such a precise protocol ensured the persistence of the implant after 10 years in 95% of cases. (Guillaume, 2016)

Setting the groundwork for this investigation, the following source provides background information on the original freehand placement of dental implants without in-depth comparisons of flawless or mini flap procedures (no exposure of bone through incision versus incision on the gingiva mask to expose the bone, respectively). A thorough understanding of the fundamental process undergone by following the current standard of treatment for dental implants (freehanded surgery) is necessary to pinpoint the limitations of the procedures. Limitations to the literature review, in particular, include a lack of insight on the precision of dental implants placed with no assisted technology, only distinct X-ray images hinting at possible deviations of dental implants compared to others placed aside. For example, Figure 7. A. presents A panoramic radiograph after eight implant placements, where the second implant placed (viewing from left to right) seems to deviate slightly from the position of the others, demonstrating a positive risk of misalignment between upper and lower dental arches when the prosthesis is placed. Although tooth loss and restoration are not life-threatening conditions or procedures, ensuring the best quality of services is essential due to its frequent presence among athletes and older patients. As the source describes the treatment's creation during the 1960s, it is evident that the standard of treatment and care should be modified to keep abreast of medical advancements in maxillofacial surgery. Literature beginning from the 2000s presents 3D printed surgical guides for placing implants to provide a faster and more accurate alternative for freehand surgery, especially in complex cases featuring patients with several implants placed simultaneously. Providing accurate and robust background information on entail implantology improves the understanding of shortcomings in the current standards of treatment and care in dental implantology while simultaneously setting up criteria for advancements to follow, such as accuracy, infection levels, mobility, and survivability of the dental implant.

A Comprehensive Review on 3D Printing and Virtual Surgical Planning

By seamlessly integrating 3D printing technology with virtual surgical planning, this comprehensive review highlights the transformative potential of these innovations in enhancing precision, efficiency, and patient outcomes in modern surgical practices (OpenAI, 2024). This investigation aims to demonstrate advancements in Oral Maxillofacial and Orthognathic surgeries by integrating 3D Printing and Virtual Planning Planning, which work symbiotically to provide personalized patient care, faster postoperative recovery time, and increased surgical precision. Conventional Oral Maxillofacial and Orthognathic Surgery bases surgical precision solely on the skills and experience obtained by the surgeon inquired for surgery. Surgical variability – unpredictable outcomes -henceforth, becomes inherent to oral surgery, bringing different outcomes from similar procedures: adverse postoperative complications – infections, intense pain, open wounds – and patient dissatisfaction. Integrating 3D Printing and Virtual Surgical Planning mitigates these limitations by providing minimally-invasive personalized surgical approaches and mitigating surgical variability, increasing surgical precision despite the number of similar surgeries performed. The personalization process begins by compiling a three-dimensional picture through layering CT Scans. Stereolithography, fused deposition modeling, or selective laser sintering analyze the composed file, printing out the preferred model. Stereolithography uses solidified layers of liquid resin through laser to build detailed models, known for its precision yet extended processing time. Light-cured resting techniques in Digital Light Processing offer a versatile model without time barriers. Lastly, fused deposition modeling produces models at the fastest rate, with a lower start-up and production cost, yet such models are reduced in strength, durability, and physical aspects. Through virtual surgical planning, surgeons assess the possible asymmetrical area and simulate the surgery while manipulating the 3D printed model through restructured bone pieces or positioning surgical guides to produce the desired outcome. Through personalized approaches for each patient, predictability increases as surgical guides account for anatomical asymmetries in the patient's body.

In contrast, conventional surgery tends to oversee anatomical differences, not much so in model construction, but in placement. Increased predictability correlates with higher success rates, patient satisfaction, patient satisfaction rates, and fewer postoperative complications. As Jwa-Young et al. (2023) states:

Traditional methods come with inherent risks and complications such as infection, bleeding, nerve damage, issues with wound healing, unfavorable bone segment move ment, and relapse [5,7]. In severe cases, these complications could lead to a second sur gical intervention [8] From a patient's perspective, traditional surgical methods can be intimidating due to the invasive nature of these procedures and the potential for long recovery times. Additionally, the traditional planning process may not allow patients to visualize the intended surgical outcome, leading to potential dissatisfaction with the postoperative results…Three-dimensional printing, also known as additive manufacturing, has emerged as a transformative technology in the last few decades [16]. The process involves creating three-dimensional objects from a digital file, typically by adding material layer by layer [17]. This contrasts with traditional subtractive manufacturing methods, which rely on cutting away material. Various types of 3D printing exist, including stereolithography (SLA) [18], Appl. Sci. 2023, 13, x FOR PEER REVIEW fused deposition modeling, and selective laser sintering, each with 4 of 15 its unique strengths and suitable applications by layer using a laser or a UV light source. This results in the production of intricate and detailed models. Furthermore, the SLA process enables the creation of smooth surfaces, enhancing the aesthetic appeal of the final product. However, it is important to acknowledge the drawbacks associated with SLA. One significant limitation is the relatively long processing time required for the completion of the printing process. Additionally, SLA is limited in terms of material choice, as it primarily relies on liquid resins. Moreover, the post-production step of removing supporting structures can be time-consuming and labor-intensive. In the SLA classification of 3D printing, there is a 3D printing technology based on digital light processing (DLP). DLP stands out for several reasons. Its hallmark is its unparalleled accuracy, which is manifested in the creation of models that are not only precise but also have a smooth surface finish, thanks to the light-cured resin technique it employs. The computer-generated surgical guide template, a product of this technology, emerged as a beacon of innovation, offering surgeons enhanced visualization, superior treatment planning, and outcomes that could be predicted with a higher degree of certainty. Its versatility is evident in its wide range of applications, from crafting presurgical dental models to aiding intricate surgical procedures. On the other hand, FDM offers distinct benefits that make it a popular choice in many applications. Notably, FDM exhibits a high production speed, making it suitable for rapid prototyping and small-scale manufacturing. Additionally, FDM is characterized by low startup and production costs, which makes it a cost-effective option for various industries. However, FDM has certain limitations that should be considered. One significant drawback is the poor mechanical characteristics of the printed objects, which often exhibit reduced strength and durability. Furthermore, FDM products may have a noticeable layered appearance, which can be visually unappealing. Additionally, the retained support structures in FDM prints require manual removal before the final product can be used. (Kim et al., 2023)

3D Printing and Virtual Surgical Planning implementation into Oral Maxillofacial and Orthognathic Surgery have proven to increase precision and patient satisfaction by granting surgeons a more predictable surgical plan personalized to the anatomical features of their patients. Through this meticulous process, mitigation of surgical errors leads to faster post-operative recovery, increasing patient satisfaction. Concerning the overall investigation, the data proves that technological implementation decreases problems of conventional surgery, such as surgical error and patient dissatisfaction; however, questionable cost-effectiveness hinders the implementation of this technology into the field. This investigation brings a new layer to the research by underscoring the increasing necessity for surgeons to acknowledge the significance of personalization in medical procedures rather than concentrating on the apprehension of technology replacing human surgeons. Surgeons must adapt and incorporate instruments such as 3D printing as medicine develops to enhance patient outcomes. This technology should not be perceived as a threat but rather as a means to improve the surgeon's function by integrating clinical expertise with technological advancements. The maxillofacial and orthognathic field of surgery can continue to innovate towards the development of personalization in surgery, thereby ensuring that procedures are customized to the unique requirements of each patient and fostering a more profound comprehension of the significance. Alleviating the friction between standardization and individualization in medicine through the integration of 3D printing into the fields builds the first steps toward decommercializing medicine and recuperating the main focus of medicine: to serve the people. Standards of care, such as dental implantation, must reflect the current innovations in the maxillofacial field. Further in the investigation, the comparison between free-handed and guided surgery suggests an evident need to change the current standard of care for implants - free hand - to surgical guides, specifically in complex cases involving many implants. Although the source provided focuses on the manufacturing process of making all types of 3D printing contraptions, from bones to surgical guides, its application into this investigation begins the implementation of technology as not just a technological advancement but primarily an advancement in care.

Clinical Applications of 3D-Printing in Surgery

Exploring the clinical applications of 3D printing in surgery unveils a revolutionary approach to patient-specific solutions, transforming traditional procedures with enhanced precision and adaptability (OpenAI, 2024). This investigation aims to inquire about the existing and future roles of 3D printing (3DP) in surgery, emphasizing its use in clinical practice, prospective advantages, limitations, and areas for potential enhancement. The paper emphasizes the role of 3DP in training rising surgeons in a low-risk environment to improve surgical precision through preoperative and intraoperative planning with patient-specific models. The source discusses the advantages that 3D printing grants to medicine. From meticulous surgical planning for patient-specific surgeries to reducing the learning curve in novices, 3D printing implementation has set the framework of the medical field yet to evolve. Providing preoperative preparation for complex surgeries allows surgeons to plan a surgery by the anatomy and distinct angles of the patient’s body rather than practicing on cadavers of similar yet different anatomies. By simulating a near-exact model of the patient being operated on, surgeons can predict potential challenges and visualize solutions, even before a threat is posed. By providing tactile feedback and aiding surgeons in developing spatial awareness within the body cavity, surgeons refine surgical skills in a safe setting. Having said this, the 3D model sets the stage for a safe environment, accepting mistakes and encouraging novices to learn from these setbacks without additional burdens or guilt. Physicians’ education to obtain surgical skills is often hindered by the initial risks once they are assigned to clinical practice. By preparing them in a space where mistakes can be guiltlessly assessed, novices can smoothly correct themselves and be equipped for complex surgeries. Although beginning from the 1970s, the usage of personalized three-dimensional simulation models will stay and continue to evolve as the years pass, hence the importance of making it accessible to all institutions. Cost and manufacturing time pose barriers to the implementation of standardized 3D printing. However, suggestions to share resources with departments and further modifications to producing the 3D prints have been considered. Nevertheless, despite manageable obstacles, all data foresees 3D printing as an integral assist for surgical skills. The source reveals the following insights insights:

Creating a 3D-printed anatomical model is done through a series of technical steps and implies that a few essential requirements are fulfilled. First, high-quality images must be obtained from MDCT or MRI scans to build a valuable 3DV reconstruction. The slice thickness of acquired images must not exceed 2 mm, with an optimal value below 1 mm [2, 3]. Thick slices would result in poor accuracy of the 3D model and in the loss of the finest details, e.g., small caliber vessels. The enhancement of the anatomical structures depends on the use of a medium contrast dye and on the specific contras tographic phase. Accordingly, each structure is processed in the phase in which it has the highest visibility, thus involving the use of registration techniques to restore the right spatial positioning of the structures [3]. Image elaboration for 3DP starts with a segmentation process, whose aim is to diminish the complexity of the original image by selectively marking the anatomy that is meant to be printed which is, therefore, extrapolated from the rest [3]. This is made by labelling each target structure in every single slice, by means of automatic or semi-automatic algorithms evolving within each slice and through the slices: algorithms' evolution is guided by the natural contrast of different tissue densities and by morphological parameters, e.g. the smoothness of the contours or thresholds on the grey levels. The evolution stops once the structure of inter est is completely identified. Then, segmentation labels are interpolated and a 3D rendering of the whole surface of the target anatomy is finally obtained. Such 3DV model recon struction is navigable, allowing each structure to be rotated, hidden or coloured to enhance the interaction between dif ferent parts [3]. At this stage smoothing of the surface may correct irregularities or sharp edges to ensure homogeneity and consequently high quality of the 3D rendering. In the next step, the 3DV model is exported as a sur face triangulation language (STL) file which describes the spatial geometry of the object through a series of oriented triangular facets called mesh [2, 3]; this format is the cur rent standard file format which all 3DP software can process. The smaller is the size of these triangles, the more detailed is the surface of the 3DV model [3]. At this stage, smoothing of the surface may be required to correct irregu larities or sharp edges; moreover, further elaboration of the STL file should be carried out according to the final aim of the printed object, like the creation of interlocking parts to enable the assembling/disassembling of the model which is then ready for being 3D printed. The key concept of 3DP manufacturing process is the creation of objects through a layer by layer process: the 3DV model is sliced into a series of 2D layers that are deployed one after the other by the 3D printer. This "additive" approach is the expedient by which 3D printers can manage highly complex geometries, likewise anatomical models [2, 3, 5]. 3D printers can be distinguished according to the type of deposition and curing approach (e.g. Material Jetting, Mate rial Extrusion, etc.), each implying a wide range of usable materials with different characteristics as to the degree of transparency, stiffness or deformability, mechanical strength, chromatic yield and so on [2, 11, 12] (Figs. 2, 3). In some cases, a support structure or devoted support material might be employed to support the building and can be removed or dissolved once the printing process is completed [2, 12]. In rare cases, due to the challenges in the cleaning and post-processing of complex anatomies, each structure can be printed separately and then stuck together to recreate the final object: however, this approach should be avoided due to the possible misalignments during the assembly of the 3D printed components [3]. (Pugliese et al., 2018)

3D printing in medicine, particularly surgery, is a paramount asset for potential benefactors. This investigation advances the investigation to revolve around emerging variables: improved surgical education and encouraging experiential growth. Allowing novices to rehearse, make mistakes, and learn from them in a safe environment concealed from initial fears of failure during clinical rounds. Students with access to the necessary resources can better prepare themselves by establishing a solid foundation for surgical skills compared to those who do not have access to such resources. Gaining confidence while practicing medicine is an essential foundation to be built, required for a successful future for many doctors. 3D printing in the context of dental education accelerates the process of gaining confidence and familiarity with complex procedures, building surgeons unafraid to take calculated risks. This research raises questions on the difference between conventionally planned surgery and virtually planned surgery, with the assistance of visual tools such as 3D-printed mouth models. In deepening the focus of this investigation, free-hand implantation is challenged by the use of the surgical implant guide, potentially proving once again the role that 3D printing plays as a vehicle for revolutionization within the field. Implementing 3D printed models builds strong surgical-skilled and confident novices while simultaneously minimizing surgical errors, contrary to the belief that technology reduces the skills a surgeon gains. Securing additional years of exploring the cost-effectiveness of the technology's implementation and solutions to speed up manufacturing time should be the focus of future investigations. Additionally, further exploration of the educative effects of novice 3D printing could accomplish the potential to revolutionize medicine, both clinically and educationally. By fomenting a culture of multidisciplinary mastery, technology, and free-hand skill, rising surgeons would perform beyond the standards of care established in the present day, allocating resources to improve treatment and cost-effectiveness for patients.

3D-Printing in Surgical Teaching and Assessment

Integrating 3D printing into surgical teaching and assessment is reshaping medical education, providing trainees with innovative, hands-on tools to refine their skills and enhance evaluation methods (OpenAI, 2024). This investigation aims to find the correlation between using 3D printing in surgical education, including medical school or anatomical training, preoperative planning, and surgical procedures. The source depicts three areas in which 3D printing or imagination is utilized: surgical training, anatomical education, and preoperative aid models. In surgical training, the learning curve for procedural skills and field assessment (inside the body cavity) improved, as models tend to be cleaner than cadavers, less confusing, and, in some ways, less depicting of a realistic surgical scenario. However, the foundations for surgical skills are set, separating the skill from the clinical judgment of the body in its current state. The 3DP model has improved the human body's spatial understanding, reporting better retention and greater procedural satisfaction. 3D printing in preoperative settings has been proven to shorten operating time, diminish blood loss, and decrease patient stay. Finally, the use of 3D printing in surgical education, whether in preparation for complex procedures, anatomy education, surgical skill training, and the variety of technology offered by (3DP), grants rising surgeons the ability to personalize the skills they need to improve.

Additionally, as preoperative models aided the comprehension of body awareness, so do the anatomical adulation models, intended to provide the most explicit depiction of the human body. The source states this low-cost equipment is "more accessible" to the alternate. Langridge, Momin, & Coumbe (2017) highlight the educational benefits of 3D printing implementation in the following:

Additive manufacturing, more commonly known as 3 dimensional (3D) printing, is a process that permits the rapid manufacturing of high-fidelity 3D models using a specially designed printer. The technology has seen a huge diversity of applications both within and outside of medicine and these continue to increase as printers and the associated software are improved, and the materials that can be used diversify. The interpretation of medical images has historically been limited to 2D media such as textbooks and computer screens. 3D printers allow medical images, such as from computed tomography (CT), to be converted into 3D structures.1,2 This ability is now being used within the education of health care professionals to supplant or complement traditional methods of education.2-4 Surgery remains a profession, which demands high quality procedural outcomes in combination with optimal safety outcomes, similar in some respects to airline pilots. Indeed, the airline industry has inspired the growing integration of simulation in surgical training. This is recognised as a safe and effective method of training, particularly in a climate of reduced theatre hours.5 3D printed models are a continuation of this trend, offering realistic haptic feedback, which may facilitate surgical skills acquisition. The adoption of 3D printed models into surgery is still at an early stage, but several studies have reported favourable results. In 2 separate studies of 3D models of temporal bone for dissection simulation, otorhinolaryngology trainees, and consultants responded almost universally positively to the usefulness of the models and their value as a training tool.6,7 Furthermore, 1 recent study objectively demonstrated that a model of endoscopic endonasal transsphenoidal surgery accel erated the learning curve for participants, providing further evidence of the benefits of such models. This article systematically reviews the use of 3D printing within surgical education to synthesise the rapidly expand ing literature within this field and to provide recommenda tions on how it might develop in future. Published studies were reviewed to determine the following: (1) the use of 3D printing in surgical training, (2) the use of 3D printing in anatomical education, and (3) the use of 3D printed models preoperatively to aid surgical training. (Langridge et al., 2018)

Within this investigation, the featured results demonstrate a different purpose for 3D printing within the field. Although the focus of multiple sources has been strictly on the implications of utilizing personalized surgical guides, the source expresses the role of 3D printing as an educative tool. Recurrent positive feedback regarding 3D printing has threatened the source utilized and the essence of this investigation. Low costs and unmatchable accuracy provide patient satisfaction and create a safe environment for surgeons. As little to no complications stem from guided surgery, the pressure of making a mistake is partially lifted from the surgeon's shoulders, encouraging learning without excess apprehension. Another aspect in which this source can help advance the investigation is through the effects of the technology's implementation costs. By serving as a vehicle to diminish mistakes, there is the possibility of lowering medical malpractice insurance for doctors, being a long-term cost saver.

Nevertheless, this source provides insight into where the dangers of 3D printing and surgical guides might be a surgeon's education. Questions emerging from this source advance the investigation, as the argument of whether utilizing 3D technology and surgical guides acts as an additive to surgical skill or diminishes clinical judgment on the field. Further on in the investigation, a study comparing experienced surgeons performing free-hand implant surgeries versus inexperienced surgeons performing implant surgeries through the surgical guide proves that those who used the surgical guide performed more successful implants than those who did not. However, the study does not compare surgeons on the same basis, meaning that both of the test groups remained constant (experienced surgeons) and the surgical approach changed (surgical guide usage or free-hand approach). However, it sets the foundation for future investigations to explore the difference between the two and determine the best methods for patient satisfaction. Although limited by the commercial aspects of privatized medicine in the context of Puerto Rico and the United States, these investigations propagate change within healthcare systems, encouraging them to change the standard of care for implantology to begin covering the cost of manufacturing the surgical guide, rather than just the implant itself.

These models make surgeons rigid, which, in turn, miscontextualizes what "standardized" means in surgery. Standardization does not mean "the same approach." It means equal opportunity to receive optimal care. 3D printed models resemble standardization, as their creation requires a standard process and optimal care, and the patient's needs and specific anatomy are the surgery's top considerations. The road to improving patient care begins with considering the patient, not just in bedside care, but as the focus of surgical procedures. Patients are not "fit" for surgery; surgery should be "fit" for them. By modifying the dental school curriculum and pre-operative procedural planning, the standard care for implant surgeries would shift toward personalization, and students would be trained early to consider each case's complexities rather than merely memorizing standard procedures. To contextualize this source into this investigation, the following can be stated: It is essential to row a culture of personalization in medicine, refocusing its purpose toward optimal patient care and seeking new ways to provide more optimal standards of care from every passing investigation.

Accuracy and Reliability of Digital Guided Implant Surgery

Assessing the accuracy and reliability of digital guided implant surgery highlights its potential to revolutionize dental procedures, ensuring precise placement and consistent outcomes for patients (OpenAI, 2024). This investigation aims to prove the accuracy and dependability of guided implant surgery through digital technologies such as 3D printing and Computer-Aided Design/Computer Aided Manufacturing (CAD/CAM), outlining the planning for guided surgeries as a model for others to follow. The investigation proves the decreases in surgery time, alongside increased predictability of outcomes, increasing patient satisfaction due to precise outcomes. The investigation focuses on static guided-facilitated implant surgeries, limited to the advantage of dynamic guided-facilitated surgeries, which can adjust the guide with computerized navigation systems intraoperatively. Static-guided surgery results in accurate execution due to proposer case selection and planning throughout a digital "workflow," stating the following steps as integral steps for the fulfillment of the surgery: (1) patient assessment, (2) data collection, (3) data manipulation, (4) virtual implant planning, (5) guide and prosthesis manufacture, and (6) execution of surgery and delivery of an immediate provisional prosthesis. The patient Assessment stage determines restorative status for remaining teeth, bone quality, adequate mouth opening for posterior access, and lip support to personalize surgical plans to the limitations of the patient's mouth. Data collection begins with acquiring CBCT and surface optical scanning, compensating for possible distortions between soft tissue and hard tissues. Segmentations, differentiation, and colorization of anatomical regions constitute the manipulation stage: density thresholds are used to localize the bone, and then colorization is used to identify core bones confronted in the surgery. Virtual implant planning consists of adjusting implant position according to bone availability, choosing the type of support for the guide (teeth, bone, tissue, or a combination), and designing the prosthesis (matching implants to access holes). The procedure is executed once the manufactured prosthesis ends in the hands of the surgeon.

Nevertheless, slight levels of inaccuracy in four measurements (coronal depth, angular, Cretan point, and apical point) ranged approximately from a safety margin of 2mm, subjectivity of density threshold, and surgical aids constitute factors affecting the final product. However, the precision of digital-guided surgery does not vindicate conventional surgical methods. The investigation by Firas, Al-Sabbagh, and Camenisch (2019) supports the following:

Current guided technology enables implant planning and placement in a prosthetically driven manner. The digital workflow generally consists of 6 steps: (1) patient assess ment, (2) data collection, (3) data manipulation, (4) virtual implant planning, (5) guide and prosthesis manufacture, and (6) execution of surgery and potential delivery of an immediate provisional prosthesis. However, sometimes a combination of analog and digital steps may be applied to the workflow. Guided implant surgery is assumed to be accurate, precise, and reliable compared with free-handed implant surgery. However, deviation between implant virtual plan ning and implant real position may occur because of the surgical learning curve and the accumulated errors that may occur throughout the multiple steps of the digital workflow. The reliability of computer-guided surgery does not justify a blind execution. The learning curve is undeniable and aclinician with basic surgical skills, including conventional implant dentistry, will be in a better position to address any unforeseen complications. (Al Yafi et al., 2019)

About the advancement of this investigation, the following article goes beyond restating the proven precision digital-guided implant surgery has over conventional styles of implant surgery; instead, it gifts the intended audience a road map for guided implant surgery. Through in-depth instruction for each step, the source highlights the circumstances in which that step may cause a deviation in the future trueness of the surgery outcome, trueness referring to the variability between the pre-operative plan and the post-operative results. By highlighting possible deviation-causing factors in each step, the “roadmap” guides the way and warns followers of possible dangers they must overcome. Most importantly, the source discretely bridges knowledge gaps in the source before it. The article above communicated the need for literature, discussing factors within the planning of surgery that could lead to deviations in the final implantation. The current source provides:

- a list of patient-related and surgical-related factors,
- filing up these knowledge gaps, and
- promoting deeper lines of questioning in this investigation.

Literature veered toward proving the layering of deviations carried out throughout the six stages of guided oral surgery and proposing solutions for these technological errors that guide biomechanics, robotics, technicians, and biomedical engineers in mitigating these software errors. Additional investigations demonstrating the correlation between clinical experience with guided surgery and the margin of error of performed surgeries prove whether clinicians should discern didactic training to enhance manipulation and technical skills. Rather than seek further pedagogy beyond a graduate or bachelor’s degree, far into one’s career, amendments to the Dental School Curriculum must emphasize balancing conventional oral surgery with technology-guided surgery. Later in the investigation, comments made by Oral Maxillofacial surgeon Rafael Gavilanes reveal that the learning curve is manageable, depending on the education received before entering private practice and the instructions that come with each shipment of an implant surgical guide.

Accuracy Comparison of Implant Positioning with Additive and Subtractive Surgical Guide Techniques

This study investigates the accuracy of the implant position using 3D-printed surgical guides (additive technique) versus a milling (subtractive techniques. Originally proposed as a hypothesis that there would be no significant deviations between, the results supported the hypothesis, as both models had similitudes in their precision and deviations.

The study supports the trends of using CAD/CAM or Computer Aided Design and Manufacturing respectively to improve implant placement accuracy, measured by the lack of deviation between the actual implant location and the planned position. The study indicates that most literature reiterates the similar results in accordance with the usage of surgical guides such as improving accuracy compared to freehand technique, deviation in apical portion is greater than the coronal, and tooth-supported guides are superior to bone-and-tissue surgical guides. Measured p-values, where p>0.22 define differences between the surgical approached to be statistically equal, concluding that both additive and subtractive techniques have high accuracy and clinically acceptable. A statistically insignificant different occurred in the group of 3D-printed surgical guides presented higher varibaility in bucolic-lingual angular deviation and apical deviation. Literature deemed these methods cost-effective and capable of predictive-planning to improve surgical outcomes. However, comparing in office 3D printing to out-to-office 3D-printing, in-office is less expensive, however, much less available than contracting an external company. Results of the study suggest the following regarding deviations:

Intraclass correlations indicated a high level of reproducibility of each of eight measures of accuracy, with values ranging from 0.967 to 0. 997 (p < 0.00001 in all instances).Descriptors of the eight measures of accuracy are given in Table 1. There was no evidence that the distribution of any of the measures differed between fabrication groups (p > 0.22 in all instances, Wilcoxon-Mann-Whitney test). multivariate analysis via PERMANOVA provided no evidence of a difference between the milled and printed groups (p = 0.68). None of the variances differed significantly between the milled and printed groups for any of the eight measurements. This general similarity in variability may be observed in the standard deviations given in Table 1. Two results were some- what suggestive of greater variability in the printed group: bucco-lingual angular deviation (p = 0.10) and apical deviation (p = 0.06). Multivariate assessment of variance homogeneity yielded significant results (p = 0.04), providing confirmation of the impression of somewhat greater dispersion in the printed group. (Henprasert et al., 2020)

The integration of this source within this investigation serves primordially to clarify undefined terms in preceding sources. For example, the source titled "*Second Systematic Review Surgical Implant Guide's Accuracy,"* the milling technique is not explained, leaving a gap in understanding for the methods used to print the surgical guide. Therefore, by assessing these doubt, a better insight on the limitations posed between accessibility for distinct surgical guide styles is better understood, where the 3D-printed surgical guide is composed of resin or a laminated acrylic molded by the patient model and the milled surgical guide is made by using an acrylic resign, however, it is chipped away to have the shape of the model. By understanding the process each type of guide must undergo, it can be concluded that having 3D-printed surgical models seem to be more accessible rather than milling, as milling requires specialized machinery that may not be as readily available as machinery for in-office 3D-printing. However, the source limits itself to presenting to readers the availability of each in the medical market, depriving the investigation of further solutions for surgeons seeking to adopt in-office machinery opposed to depending on external companies for the production of the surgical guides. Extending the period of manufacturing by contracting an external company to manufacture the surgical guides tend to add obstacles in patient treatment. For this reason, this investigation seeks to raise awareness around the lack of literature providing insight on the cost-effectiveness of incorporating 3D-printing materials and milling machineries into clinical practice, office environments for patient use. Modifying standards of cost-effective solutions for accessibly manufacturing methods accompany the possible modifications to the standard of treatment and care in dental implantology, hence, more literature must provide guidance for physicians seeking to revolutionize their offices. Spotlighted in this investigation is a Puerto Rican maxillofacial surgeon, where he utilizes freehand, computer-guided, and surgical guides as surgical approaches for implant placement; however, surgical guides must be ordered from external companies, such as BioHorizons, outside of the island, since machinery nor extensions of the company are found on the island of Puerto Rico.

Guided Dental Implant Surgery: A Systematic Review

A systematic review of guided dental implant surgery underscores its transformative impact on clinical precision, efficiency, and patient-centered care in modern dentistry (OpenAI, 2024). This article reviews the most recent developments in personalized implants in oral and maxillofacial surgery. It investigates the regulatory perspectives that affect these implants' planning, manufacturing, and application and offers insight into the engineering principles that were implemented during their development. The investigation also seeks to analyze the prevalence of biological complications, such as peri-implantitis. The systematic review of guided dental implant surgery assessed various studies, including patient ages ranging from 15 (Meloni et al., 2010) to 66 (Derksen et al., 2019), with comparable average ages observed across the studies. The studies evaluated data on the dental arch condition (post-extraction or healed sites), surgical approach (flap, mini flap, or flapless), tilted versus non-tilted implants, loading protocol (immediate or conventional), and the time until final restoration placement. All studies, except for Derksen et al. 2019, utilized immediate loading, while others employed conventional loading in the other featured studies. Although implant failures occurred within two weeks to three years following surgery, the survival rate of implants ranged from 96.3% to 100%. Marginal bone loss demonstrated variability, with a minimum of 0.32 mm recorded one year after implant placement, considered acceptable, and a maximum of 1.9 mm observed in more extended follow-up periods. The results suggest that guided implant surgery exhibits high survival rates; however, complications and bone remodeling issues may arise over time. The systemic review highlights the following results from their investigation:

The data on peri-implantitis and, more generally, on the biological complications are reported [in Table 6]. The most commonly reported post-operative biological complication, which is also the final event that leads to the loss of the implant, is the lack of osseointegration. The presence of peri-implantitis is reported in at least 4 studies and appears to be the main complication. An additional consideration should be made on the consumption of smoked tobacco, it should be noted that the early loss of the implant due to lack of osseointegration occurred in smoking patients in at least 3 studies. (Dioguardi et al., 2023)

This source offers pivotal insight into the implementation of guided implant surgery in the Oral Maxillofacial field in the context of trying to provide personalized care with a standardized protocol. Through detailed criteria on all patients regarding the procedures gone through to print out an accurate surgical guide and the usage of software technology and CT scans to extrapolate accurate and personalized data, the surgical implant guide is the first step toward demonstrating the efficacy of this principle in medicine overall. As the treatment and approach become more personalized, there is less margin of error and greater success of the surgery. Future research should focus on other areas of medicine using customized 3D modeling and surgical planning tools to develop treatment plans that are standardized in protocol but individualized in implementation based on distinct patient characteristics. In this investigation, they highlight the importance of high bone stability and implant survival rates, meaning that through proper placement of the implant, enhanced by the surgical guide, osseointegration between the implant and the bone must be seen through the scans.

The source considers that for proper adherence to the guide's protocols, high initial costs of software, CT scans, and companies responsible for manufacturing the guided models are necessary. However, its benefits (less invasive news, lower complication rates, fewer failures) contribute to a lower long-term cost; hence, the 3D printing and software technology is a high-yielding investment for future cuts to cost and higher success rates in osseointegration - the direct bond between the implant and the bone.

Second Systematic Review Surgical Implant Guide's Accuracy

A second systematic review of surgical implant guide accuracy delves deeper into the precision and consistency of these tools, reaffirming their critical role in enhancing implantology outcomes (OpenAI, 2024). This review aims to explore the accuracies of static digital surgical guides in the following areas: guide supporting types, manufacturing methods, and design of dental implant guides. To provide a reference for future elaboration of digital genial implant guides, the investigation aims to reveal the technology's influence on surgical accuracy and precision. The accuracy of dental implant placement involves both trueness and precision, with trueness specifically indicating the deviation between the postoperative positioning of the implant and the preoperative plan. A standardized evaluation guide for implantation needs to be improved, with assessments generally focusing on coronal, apical, depth/vertical, and angular deviations. The scanning process for implant planning demonstrates greater accuracy in intraoral impressions compared to extraoral ones, with evaluations typically relying on CBCT scans. The analysis differentiates between static and dynamic surgical guides, concluding that flapless surgery usually results in higher accuracy than flap surgery. Fernando Bover Ramos (2018) observed that in vitro studies exhibited greater accuracy than clinical and cadaveric studies, with fully guided surgical guides proving to be more precise than their half-guided counterparts. This review examined 41 studies—21 conducted in vitro, 19 in vivo (which included two cadaver studies), and one focused on accuracy comparison. The breakdown of 17 clinical studies includes three case-control studies, 11 clinical trials, and three cohort studies. An assessment using the Newcastle-Ottawa Scale (NOS) on the 20 in vivo studies revealed three medium-quality and 17 high-quality studies; this indicates robust sample selection and statistical analysis, although only three studies had sufficient follow-up. The review features a detailed table that presents deviation data (global/horizontal, coronal, apical, angular, vertical) expressed as mean ± SD or median (min, max). It also includes forest plots and normal distributions that illustrate accuracy-related deviations and comparison criteria, such as support types, fixation screw designs, sleeve designs, and surgical guide manufacturing methods. Tooth-supported guides emerged as the predominant type, with 27 studies focusing on bilateral guides, nine on mixed tooth/bone or tooth/mucosa configurations, and seven on mucosa-supported guides. For bilateral tooth-supported guides, global coronal deviations were reported as 0.1–1.18 mm (in vitro) and 0.46–1.47 mm (in vivo), with additional deviations noted for horizontal coronal (0.18–1.37 mm in vitro / 0.39–1.07 mm in vivo), global apical (0.12–1.95 mm in vitro / 0.28–1.77 mm in vivo), horizontal apical (0.31–1.68 mm in vitro / 0.64–1.17 mm in vivo), angular (0.77–7.713° in vitro / 1.4–4.74° in vivo), and vertical deviations (0.11–0.95 mm in vitro / 0.03–0.84 mm in vivo). Unilateral guides exhibited global coronal deviations of 0.284–1.43 mm (in vitro) and 0.21–1.2 mm (in vivo), whereas mucosa-supported guides showed deviations from 0.45–0.82 mm (in vitro) to 0.98–1.987 mm (in vivo). Only two studies conducted comparisons of sleeve lengths, and three studies evaluated guides that incorporated fixation screws. Of the 41 studies, 29 employed 3D printing techniques, three utilized milling processes, and six did not disclose their fabrication methods. The source highlights that:

> To verify the hypothesis that supporting types influence the accuracies of surgical guides, we collectively categorized and analyzed guide type and deviation data in existing literature. Implant guides are divided into cat egories according to its support types, including bone supported, mucosa-supported, tooth-supported, and any combination (Fig. 3). Theoretically, the anatomical differences among teeth, bone and mucosa may lead to different accuracy of guides with different support types. Bilateral tooth-supported guides provide best retention and biomechanical stability with anchorage on hard tis sue, therefore theoretically endow highest accuracy. Although with advantages in accuracy and operability, bilateral tooth-supported guides are indicated for patients with intact teeth both mesial and distal to the edentulous area. As for distal extension edentulism, one of the most common clinical manifestation, unilateral tooth-supported guides including mixed tooth-/bone- or tooth-/mucosa-supported guides are often used to pro vide efficient retention. Bone-supported guides are overlaid on the alveo lar crest exposed via full-thickness mucoperiosteal flap operation and fixed with fixation screws. Its larger surgi cal wound, upturned tissue flap affects its repositioning, resulting in relatively low theoretical accuracy. Simple bone-supported guides are seldom reported in recent five years [62], and among the 41 researches included in this review, only two studies applied mixed tooth-/bone-sup ported guides [63, 64]. Mucosa-supported guides are indicated for completely edentulous patients or patients who barely have residual teeth. Without flap operation, it is anchored to the bone through the mucosa with fixation screws. To be noted, a recent research reported that calculation of implant angular deviation of mucosa-supported guides by tissue or implant alignment resulted in different values [41], emphasizing the lack of standard for accuracy measurement, and indicating that comparability of the accuracy indicator values in different literatures should be reviewed dialectically. (Shi et al., 2023)

This study stresses the potential of computerized surgical guidance to enhance personalized patient care by customizing implant placements. These technologies facilitate the customization of therapies to meet specific anatomical requirements, thereby minimizing space for errors. Implementing standardized procedures in formulating and applying these guidelines guarantees that individualized treatment is uniformly provided across diverse patient populations and clinical environments. The equilibrium between personalizing therapies for individual patients and adhering to established protocols advances the field, enhancing patient outcomes while ensuring safety and regulatory compliance. The review emphasizes the continual standardization of criteria regarding accuracy achieved through the digital implant guides to extrapolate replicable standardized data. Advancing literature regarding digital surgical implant guides must establish standardized criteria for testing accuracy and trueness to comprise a robust pool of information from which other surgeons can benefit. By creating more reliable information, surgeons or professionals, in general, could more confidently implement these technologies into their field without the fears of doubt and deregulated information.

Comparison of Accuracy between Free-handed and Surgical Guide Implant Placement

Comparing the accuracy of free-handed implant placement versus surgical guide-assisted techniques highlights the significant advancements in precision and reliability achieved through guided methods (OpenAI, 2024). The research sought to evaluate the precision of dental implant placements by contrasting experienced operators doing freehand surgery with inexperienced operators utilizing static-guided surgery, determining if a surgical guide mitigated the disparity in implant placement accuracy between experienced and novice practitioners. The study reinforces its methodology by emphasizing the importance of precision in dental implant placements, considering the anatomical complexities of each patient's maxilla area. Precise placement reduces complications and achieves optimal aesthetic and functional results. Given the difficulties associated with freehand procedures, particularly for novice practitioners, implementing guided technology could standardize outcomes and enhance patient results. This experiment employed 20 acrylic models, including 60 implants, each featuring three. The freehand method and a 3D-printed surgical guide were used to position 30 implants each. Two groups, each consisting of five operators, were selected based on their skill level. Each operator placed three implants using the freehand approach and an additional three implants utilizing a surgical guide. The results demonstrated that untrained operators placed implants using a surgical guide with greater precision than competent operators. Lateral deviations regarding implant 11 (crest) Of the freehand (experience) was 0.68 mm with a standard deviation of 0.25 mm. The guided experience displayed a 0.14 mm difference with a standard deviation of 0.15 mm.

Regarding the Apex on implant 11, the free hand displayed a difference of 1.04 mm with a standard deviation of 0.33 mm compared to the guided, which had a difference of 0.52 mm with a standard deviation of 0.10 mm.

Regarding implant 22 (crest), the freehand displayed a difference of 1.30 mm with a tiny deviation of 0.41 mm, while the guided portrait showed a 0.22 mm difference with only a standard deviation of 0.04 mm. On implant 22 (Apex), the freehand displayed a 2.46 mm difference with a 0.82 mm standard deviation, while the guided only had a 0.22 difference from the planned location with a standard deviation of 0.13 mm. A pickle displacement on implant 22 regarding the guided was 2.00 mm with a standard deviation of 0.4 mm. In comparison, the freehand and experience displayed a difference of 3.18 mm from the originally planned location. Finally, the angular deviation for the freehand (experienced) displayed an N 85.8° mean, while the guided (inexperienced) displayed an angulation of 86.6°. More about the data is presented as the following:

In this experiment, 20 acrylic models with a total of 60 implants were used (3 implants per model). The free-hand technique and a 3D-printed surgical guide were used to place 30 implants each. Two groups of 5 operators each were selected based on experience level, and each operator placed 3 implants using the free-hand technique and another 3 using a surgical guide… The implants placed using a surgical guide showed less variation in all metrics compared to the implants placed using the free-hand technique. The 2 approaches showed statistically significant differences. For implant number 11, the lateral deviations (mesiodistal) in the free-hand group were significantly larger, both at the crest and apically. The mean difference between the distal surface of implant number 11 and the mesial surface of tooth number 12 at the crest was 0.68 mm (SD: 0.25 mm) for the experienced group using the free-hand technique and 0.14 mm (SD: 0.15 mm) for the non-experienced group using the surgical guide (P=0.019). The mean difference between the mesial surfaces of implant number 11 and tooth number 21 at the apex of the implant was 1.04 mm (SD: 0.33 mm) for the experienced group using the free-hand technique and 0.52 (SD: 0.10 mm) for the inexperienced group using the surgical guide technique (P=0.044). (Hama & Mahmood, 2023)

Concerning this investigation, the source proves that guided implant surgery goes over freehanded surgery by mitigating errors from planned implant positioning. Each aspect tested - angular deviation, lateral deviation, and apical displacement - deviated less from the expected implant, while the freehand demonstrated its tendency to deviate farther from the ideal location. Using an implant guide significantly enhances the likelihood of success, particularly in complex surgeries; this highlights the importance of incorporating guided techniques to improve outcomes in implantology and ensure more patients receive effective treatment options. As cases become more complex, meaning that more implants must be placed simultaneously, the guide is a paramount tool that surgeons can utilize to ensure their work is successful. While complications in surgery can arise from a lack of experience or occasional mistakes, it is crucial to recognize that guided surgery helps minimize the risk of surgical errors due to inexperience. The standardization of guided surgery in implants ensures that each patient is treated to the standard of care regardless of the surgeon's experience.

Interview with Puerto Rican Oral Maxillofacial Surgeon

An insightful interview with a Puerto Rican oral maxillofacial surgeon offers a unique perspective on the advancements and challenges in modern implantology and surgical practices (OpenAI, 2024). This source features a natural facial surgeon working in Aguadilla's municipality on Puerto Rico island. A series of questions were generated regarding the different variables that come into play when investigating the application of guided implant surgery in the field of Maxillofacial surgery. The interview encompasses concepts such as cost-effectiveness, durability, patient outcomes, learning curves, and discussion regarding the standard of care in place for implant surgery. Beyond the interview, a field observation was conducted to observe a full spectrum of building personalized surgical guides. From patients beginning to heal from tooth extractions and planning their next implant to patients getting their screws situated after months of healing the osseous tissue of their mandible, the field observation deepened the awareness of the benefits of integrating this new technology more widely.

Regarding the cost-effectiveness of the implant, the surgeon responded that it mitigated the complications associated with implant placement in terms of angulation, lateral deviation, apex deviation, and axial deviation. Additionally, it reduces operating time.

The surgeon stated that in a hypothetical situation where he had done the surgery freehand, it would have taken him about 45 minutes to complete the task; however, with the guided surgery in 10 minutes, the implant was already set. The surgeon responded that since their insurance covered the implant already, the additional charges for the construction of the surgical guide were, in his perspective, a beneficial investment into the long-term durability of the implant. The coverage for a dental implant, covered by the patient's health insurance, reaches about $2,400 in this patient's case, making the additional charges to complete the surgical guide minuscule. The total cost for the guide, ranging from $450-$700, is distributed between each step of the process: virtual planning meeting, $50; design, $100; treatment plan post-op, $100; and the resin surgical guide, $125. In essence, the surgical guide, manufactured by BioHorizons, costs only $125, compared to the implant itself, costing thousands of dollars, demonstrating the high-yielding investment into ensuring the durability of the new tooth. When patients came looking for implants, their case was usually studied thoroughly. If it was excessively complex and a challenging approach, a surgical guide was an immediate consideration. However, in the case of a simple implant, the surgical guide was not considered; in the case of more complex cases, the surgeon explained the procedure thoroughly, explaining to the patient the need for the guide. The decision to create the surgical guide hinges on the severity of the case, the number of implants to place, and how precise the teeth' position must be. Even then, the guide's cost-effectiveness stems from using CBCT scans (less expensive imaging systems) and decreasing operating time. As the duration of the operation diminishes, pain reduces as less stress is placed onto the mouth, inflammation subsides, and anesthesia's effects wear off more quickly. Combining all these beneficial factors presents another aspect of cost-effectiveness: a reduced likelihood of revision surgeries. Initially proposed by the investigation as a hindrance in the establishment of surgical guides as a standard of care, the learning curve for mastering the usage of surgical guides for implantology is overcome by the accessibility to clear, visual, and detailed instructions for the process of placing an implant using the kit provided by the manufacturer making the guide. Discussion of modification to the standard of care of implantology inevitably arose, revealing the possibility of evolving from freehanded surgery to guided surgery without total dependence on the surgical guide in the case of flaws with the surgical guide itself. The following questions guided the compilation of questions and answers from the interview:

Question 1: Has dicho que en términos de costos efectivo, es costo efectivo el guía, por que?

Interviewee: Es costo efectivo porque número uno reduce verdad Lo que son las complicaciones asociadas a poner los implantes. Y número dos, porque puedes hacer los implantes más rápidos. Así es que, por ejemplo, ese implante, esos dos implantes. Si yo los hubiese tenido que hacer a ojo, quizás me echaba, no sé ni cuánto me tomó hacer eso. Quizás me tomaba, qué sé yo, 45 minutos. Y con eso, en diez minutos. O sea, así es que si al final termina siendo definitivamente costo efectivo.

Question 2: ¿Y para el paciente?

Interviewee: Pues si él tiene que incurrir en un costo extra, verdad que es la creación de la guía, pero pues número uno, verdad, la rapidez no tan solamente ayuda, me ayuda a mí como doctor verdad. Al yo poder ver más pacientes y hacerlo más costo efectivo en la cirugía. Todas las secuelas de la cirugía, el dolor, la hinchazón,la molestia, está todo también relacionado al tiempo de cirugía. Así es que si tú disminuyes el tiempo de cirugía en gran medida también va a disminuir todo lo que es el periodo operatorio del paciente, o sea, va a tener menos dolor, menos hinchazón; todas esas cosas. Así es que, sí. Aunque él incurre en un gasto, pues también tiene beneficios para él. No es tan solo para el cirujano como tal.

Question 3: ¿Ustedes hacen un plan de pago?

Interviewee: O sea, la mayor parte de los pacientes que tú estás viendo son pacientes de plan médico. Así es que a esos pacientes, el seguro médico les está cubriendo sus implantes. Así es que básicamente le sale lo que le sale gratis, porque ellos pagan el plan médico. Pero su plan médico cubre esa parte. Y lo único que ellos tienen que pagar, pues entonces es el guía como tal.

Question 4: ¿Entonces, el poner un implante depende del presupuesto del paciente o del caso como tal?

Interviewee: No, o sea, yo no baso la decisión de hacer una guía en términos de costos, verdad, o lo que el paciente puede pagar. O sea, hay muchos casos que sí es un implante sencillo o si son implantes, que se yo, para una sobredentadura, que son los dos que se ponen aquí para poner una sobre dentadura. Todo eso, independientemente de si el paciente lo puede costear o no, o sea, si son implantes que yo voy a hacer a ojo, no los voy a hacer guiado. Simplemente los casos que yo hago guiado son casos que por alguna razón u otra tienen que quedar bastante perfecto o bastante paralelo, o son casos en la mayor parte verdad que son de múltiples implantes. Así es que, pues, eso complica la cosa un poco más y el tener una guía pues te hace ponerlo de la manera correcta. Así es que ,sí, en términos generales veo más sin la guía, pero es porque yo decido hacerlo sin guía. Si hay un caso que tiene que ir guiado, pues yo lo discuto con el paciente, lo hablamos y eso. Y si él no puede costear la guía, pues se puede hacer sin guía, pero tiene que entender que hay un riesgo asociado. O sea, yo no los voy a poder poner perfectos sin la guía y puede ser que pues haya que arreglar algo en el futuro o que no queden tan bien, por decirlo así.

Question 4: ¿Cuánto tiempo dura hasta que te hagan el guía?

Interviewee: Pues el proceso de hacer la guía. Yo voy a hacer ahí, en ese sitio web, voy a hacer un “upload" de lo que es la imagen de radiografía del paciente. Hago un “upload" de lo que es la imagen del de los dientes del paciente. Entonces ellos hacen un merge. Después de eso, hacemos una reunión virtual en la cual pues los dos vemos dónde van a quedar los implantes, decidimos como los queremos y toda esa vuelta y luego de eso entonces se hace la guía el proceso de fabricación de una guía. Esta es la menos de una semana. Claro, si en verdad no es una compañía aquí, en Puerto Rico, también eso. Eso es lo que tarda un día en hacerse. Pero puede estarlo un poco más por la reunión que hay que hacer y que la empaquen.

Question 5: ¿Cuánto tiempo te tomo aprender como usar el guia?

Interviewee: Lo que pasa es que yo, dentro de la era en que me entrené, cuando fui a la residencia, ya esa tecnología existía. Así es que en realidad pues me entrené con ella. Pero no es un proceso tampoco que es difícil y como viste, o sea, te puedes llevar esto si tú quieres, literalmente aquí te dice todo lo que tienes que hacer, o sea, vas a hacer el implante, usas ese taladro. Y como tu viste, o sea, lo pones pa pa, pa. Si, si, si, si, pa. “Cualquier persona” lo puede poner así es que si el “learning curve" no es, no es un “learning curve". Poner el implante no es difícil, lo difícil es seleccionar el paciente, saber cuando va a usar eso, planificar el implante de una manera correcta. Todo eso es lo complejo, el ponerlo como tal, o sea ponerlo es una técnica que cualquier persona aprende.

Comment for Discussion: No sé muy bien el “standard of care”, pero es como que el debate de que la medicina tiene que ser estandarizada pero a la misma vez personalizada. El guía sería como que un balance, porque lo que está estandarizado es como que el procedimiento y lo que es personalizado es como que el que va de acuerdo a los estándares.

Interviewee: Pero entonces lo importante también es entender en todas estas cosas, porque en realidad tú lo estás viendo a microescala, pero nosotros hacemos. O sea, esto de hacer una cirugía virtual y tener una guía y que se yo, nosotros lo aplicamos para todas las cirugías que nosotros hacemos, la cirugía ortognática, cirugías de TMJ donde haya que poner una prótesis y cortar el hueso. En verdad todo eso aplica y eso es lo que diferencia un cirujano versus el otro. ¿Por ejemplo, si la guía no servía, cómo puedo poner esos implantes? Pues ahí tengo que yo saber poner implantes o si la guía falla en algo, tengo que saber reconocerlo y yo corregirlo. Así es que hay veces que no sale todo perfecto y ahí es donde tú necesitas, como que el expertise de ser cirujano y saber cómo hacer las cosas sin la ayuda de la tecnología para entonces poder complementar. Complementar, si ese fuese el caso, exacto, pero si puedes ponerlo así. O sea, el estándar es el procedimiento como tal, y si lo que varía de paciente a paciente es eso, el diagnóstico y el plan de tratamiento. O sea, como que la planificación de cómo hacerlo está bien ya así. (Gavilanes, Interview with Puerto Rican Maxillofacial Surgeon 2024)

The interview and fieldwork provide a holistic review of the use of surgical guides in implantology, providing a direct perspective of the technology's first-hand users: surgeons. Distinct from the objective reasoning offered by the above sources, this information outlet presents a subjective yet practical perspective of using the surgical guide. For maxillofacial surgeons like them, surgical implant guides have cut time in the office, improving his ability to consult more patients while not sacrificing accuracy within implant surgeries. By assuring near perfection while placing the implant, through the surgical guide, they have been able to operate on patients needing up to eight implants effortlessly, where no amount of complexity places an obstacle to the precision of the implants. The importance of this source in the context of this investigation answers an essential research question: How would the learning curve for rising surgeons look like with the implementation of surgical guides into the standard of care? A thorough discussion with the maxillofacial surgeon revealed that learning to perform an implant surgery with a guide is simple. An in-depth pamphlet with instructions and color-coded tools makes "any person" apt to perform the surgery. Of course, only some people can perform the surgery. No average person would willingly want to drill holes into a person's gums. That is why maxillofacial surgeons exist; they have a hint of crazy in them. In the event of a flaw in the surgical guide, the maxillofacial surgeon must employ their knowledge to either modify the resin of the guide or perform the surgery free-hand. Free-hand is currently viewed as the standard of care for implantology, making using a surgical guide almost a rarity in most cases surrounding the positioning of a single dental implant. However, as discussed with the maxillofacial surgeon, there are more effective options. There are deviations regardless of the years of experience, primarily due to the variability in patients' mouths. Approaches vary, and osseointegration is not ensured, making the survivability of an implant unpredictable. The surgical guide proposes a solution by standardizing the steps taken to build a surgical guide concordance with a unique case: a perfect balance between standardization and personalization.

Methods

This study employed an iPad with internet access and a web browser (Safari). Google Scholar was essential for identifying the sources needed to clarify the research issue in this investigation. To locate relevant sources, the search engines Google Scholar, EBSCOhost, PubMed, and the National Institute of Health were instrumental in helping to pinpoint peer-reviewed articles pivotal for answering the research questions. Additional resources, such as OpenAI's ChatGPT and QuillBot, were employed to proficiently reword the content, enhancing its clarity and originality while establishing a coherent structure for the arguments and ideas to improve readability. The resources above also aided the process of source-seeking and identification by offering effective techniques to identify reputable and pertinent sources. Despite occasional instability in the internet connection, it was adequate to facilitate all necessary components of this inquiry. Despite specific sources lacking peer review, the research mentor evaluated and sanctioned them, affirming their legitimacy. All these components functioning collaboratively established the ideal conditions for the completion of this project.

This study employed a qualitative field observation and documentary analysis design. As part of the selected methodologies, an interview was conducted to extrapolate qualitative data to assess limitations in investigating the practical implications of 3D-printed surgical guides. Ten sources were selected and analyzed utilizing a documentary analysis, each contributing unique insights into the benefits, limitations, and accuracy of 3D-printed surgical guides in maxillofacial surgery. Each source's objective, intended audience, methodology, and results were recorded through a descriptive content analysis approach. The data collection process involved synthesizing the primary concepts from each source to assess the technology's efficacy in improving implant precision and training outcomes.

Results & Limitations

The primary search engines, PubMed and the National Institute of Health, were the most effective for locating credible sources. Of the ten sources used, three were very recent, published between 2021 and 2023, each highlighting advancements in surgical accuracy and improvements in patient outcomes through 3D-printed surgical implant guides (Jwa-Young et al., 2023; Dioguardi et al., 2023; Shi et al., 2023). A recent source, Hama, D. R., & Mahmood, B. J. (2023) elucidates the importance of guided surgery for novice and experienced surgeons, illustrating its potential to set a new standard in implantology. However, the interview by Gavilanes, M. (2024) constitutes the earliest source and provides insight into the practical application of surgical guides, beginning with the procedure to manufacture the surgical guide until the positioning of the guide onto the patient. Aside from a discussion, a field observation was conducted, presenting images of the surgical guide used throughout each step of the implantation to support the reasoning behind diminishing operative time, surgical errors, and postoperative pain. Sources Firas et al., 2019 and Pugliese & Marconi, 2018 offered recent perspectives on the role of 3D-printing in clinical settings to plan operations and in educational settings, enhancing dental education through model accessibility; while Henprasert et al., 2020 compared additive techniques and subtractive techniques to building a surgical guide for patients, concluding that there was no statistical difference between each's accuracy and precision. Not recent source, Ansmann, L., & Pfaff, H. (2017) examined the broader context of individualized standardization in healthcare, which is fundamental to advancing the investigation's intentions to bring to light the importance of personalization within a standardized procedure, followed by the not recent source - Langridge, B., Momin, S. and Coumbe, B. (2017) - which highlights the beginnings of 3-dimensional printing into the realm of teaching, working to enhance surgical skills and operational approaches.

However, notable limitations were affecting both internal and external validity. Internal threats included the need to refine the research question to ensure a broader selection of sources and to replace sources that did not meet quality thresholds or failed to regain access due to database restrictions. External limitations involved occasional internet instability and limited access to specific databases, slightly restricting source accessibility. While the articles provided extensive information on surgical accuracy and procedural benefits, only one source tested the long-term outcomes of 3D-printed guides on implant stability and patient satisfaction. Most importantly, while some sources repeated the general "high-investment cost" for the manufacturing of the surgical guides, the interview solely provided insight into the actual cost of the surgical implant guides for patients and surgeons; however, this perspective is limited to the case of that Puerto Rican Maxillofacial surgeon, hence, cant be applied on a broader scale due to the variability between dental offices. Sources Pugliese, L. and Marconi, S. (2018), Langridge, B., Momin, S. and Coumbe, B. (2017) did not answer any research question stated in the preliminary research, yet brought a broader perspective about the applications of 3D printing into other aspects of the medical field; therefore, answering research questions formulated throughout the investigation, precisely the second research question. Ansmann, L., & Pfaff, H. (2017) set the foundation for the proposed research questions and the theoretical framework behind the content analysis and answers to the research questions.

Research Questions & Answers:

1. In what ways does the utilization of 3D printing and surgical guides improve the precision of dental implants?
    - According to Firas et al. (2019), 3D-printed guides reduce lateral and angular deviations in implant placement, significantly enhancing precision over free-hand methods.
2. What are the possible effects of utilizing 3D-printed surgical implant guides on minimizing mistake rates in maxillofacial procedures, and how does it impact the learning curve for novice maxillofacial surgeons?
    - As noted by Pugliese, L. and Marconi, S. (2018), 3-D printed anatomical models enable inexperienced surgeons to perform complex surgeries with conditions similar to that of real-life operations in a low-risk environment, thereby easing the learning curve through facilitated teaching. The interview conducted perceives the surgical implant guide as a tool almost "anyone can use," as the specific model the Maxillofacial surgeon utilized comes with instructions included. Further images, located in the index, demonstrate the color-coded screws to their correcponding chucks, making the procedure to place the implant quicker and more accurate.
3. In what ways does the use of 3D printing technology in maxillofacial surgery transform existing standards of care, and what are the cost implications of implementing 3D-printed surgical guides in routine practice?
    - Jwa-Young et al. (2023) discuss the high initial investment required for 3D printing and planning software, though the technology ultimately reduces long-term costs through increased procedural efficiency and reduced surgical errors. The interview, however, provided concrete data regarding the cost of the production of the guide, a non-guided implant, and the costs for the surgeon. The surgical implant guide's implication on the standard of care for implantology was hypothetically answered through the interview, the surgeon stated that there exited the possibility to change free-hand to guided implant surgery, yet no literature has supported this proposition.

Discussion, Conclusion & Future Directions

The sources reviewed underscore that 3D-printed surgical guides have the potential to transform maxillofacial surgery. By enhancing implant precision and supporting individualized patient care, surgically guided implants are transforming the standard of care, putting into question the efficacity of free-hand placed implants. Firas et al. (2019) and Dioguardi et al. (2023) present persuasive evidence on the technology's ability to improve angular and lateral precision, effectively tackling the ever-present difficulties associated with free-hand techniques. Ansmann and Pfaff's (2017) perceive a need for individualized standardization in medical procedure and treatment, building a theoretical framework that situates the significance of integrating individualized patient models with standardized protocols and post-operative treatments. Although Pugliese and Marconi's (2018) successfully presents the educational value of 3D printing to reduce barriers for acquiring surgical skills and learning operational approaches, the interview with the Puerto Rican Maxillofacial surgeon (Gavilanes, M., 2024) highlighted the reduction in the learning curve for novice surgeons through the use of the implant guide, as each of their models manufactured comes with a compilation of instructions for its use in the surgery.

For future research, a mixed-methods approach could provide deeper insights into both the quantitative improvements in implant precision and the qualitative experiences of surgeons and patients. Additionally, longitudinal studies on patient outcomes post-implantation would be beneficial for understanding the technology's impact on long-term implant success. A lack of proposed project plans to involve 3D printing and virtual surgical planning into oral maxillofacial and orthognathic surgical offices predict the expected costs businesses must make to incorporate this technology, giving insight into financial planning for future surgical methods. Additionally, providing financial aspects of the project allows offices to decide to either hire biomedical engineering companies to run the virtual surgical planning meeting, build the models, and send them to the clinics or, if acquiring the machinery, with additional charges for software training, is a more cost-effective option. Additionally, this investigations prompts longitudinal research to explore the improvement of the quality of materials and manufacturing methodologies, contextualizing the role of cost-effectiveness and quality of the implant. Clinics and hospitals considering the integration of 3D-printed surgical guides as a modern standard of care may benefit from a prospective comparative study on the cost-effectiveness of guided versus free-hand surgery in a variety of clinical contexts. Future studies could potentially explore the degree to which a patient may benefit more from a suirgal implant guide, compared to a free-hand procedure, setting up clearer parameters within the standard of care of implantology.

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