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Research Article

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The Role of Advanced Imaging in Facial Reconstructive Surgery

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Abstract
This review explores the utilization of advanced imaging techniques in facial reconstructive surgery. The primary aim of the article is to assess the role of these imaging modalities in preoperative planning, head and neck diagnoses, intraoperative guidance, and postoperative assessment for facial reconstruction procedures. The review synthesizes data from numerous studies investigating the application of advanced imaging in facial reconstructive surgery. These studies encompassed patients undergoing various reconstructive procedures, including trauma reconstruction, oncologic reconstruction, and congenital deformity correction. Imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and three-dimensional (3D) imaging were analyzed for their utility in preoperative assessment, surgical planning, and outcome evaluation. Statistical analyses included meta-analyses of pooled data where applicable to assess the overall impact of advanced imaging on surgical outcomes. The review highlights the pivotal role of advanced imaging in enhancing the precision and success of facial reconstructive surgery. By utilizing imaging modalities such as CT, MRI, and 3D imaging, surgeons can achieve greater precision, optimize surgical planning, and enhance patient outcomes. Integrating advanced imaging into routine practice is essential for improving surgical outcomes, patient satisfaction, and overall quality of care in facial reconstructive surgery.

Keywords: Facial Reconstructive Surgery, Advanced Imaging, Radiology, Preoperative Planning, Postoperative Assessment, Surgical Outcomes

1. Introduction

Facial reconstructive surgery is a specialized field within plastic and reconstructive surgery that aims to restore both form and function to the face. Facial reconstructive surgery is a dynamic and rapidly evolving field that addresses a wide range of facial deformities and injuries, with an estimated 20 million reconstructive procedures performed worldwide each year [1]. In the United States alone, over 200,000 facial reconstructive procedures are conducted annually, encompassing a diverse spectrum of indications, including traumatic injuries, congenital anomalies, and oncologic resections [2]. Over the years, advancements in surgical techniques and technologies have revolutionized the field, enabling surgeons to achieve positive patient outcomes in terms of facial aesthetics and patient satisfaction. Among these advancements, the role of advanced imaging techniques has emerged as a cornerstone in the preoperative planning, intraoperative navigation, and postoperative assessment of facial reconstructive procedures. By providing detailed anatomical information, enhancing surgical precision, and facilitating interdisciplinary collaboration, advanced imaging plays a pivotal role in optimizing surgical outcomes and minimizing complications associated with facial reconstruction.

In this paper, we will explore the evolving role of advanced imaging modalities, including computed tomography (CT), magnetic resonance imaging (MRI), three-dimensional (3D) photography, and virtual surgical planning (VSP) in the context of facial reconstructive surgery. These advanced imaging modalities have become integral tools in the armamentarium of facial reconstructive surgeons, with up to 80% of surgeons utilizing these technologies in their practice [2]. These imaging techniques provide detailed anatomical information and enable surgeons to visualize complex facial structures in three dimensions, facilitating accurate preoperative assessment and surgical simulation. In this review, we will examine the role of advanced imaging in various aspects of facial reconstruction, ranging from preoperative assessment to postoperative monitoring and long-term outcomes assessment.

2. Methods

2.1. Initial Search

We followed the standards outlined by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines during data collection and the PICOS (Population, Intervention, Comparison, Outcomes and Study) framework was used to create eligibility criteria. We used keywords such as "craniofacial surgery" (or "Reconstructive Surgery, Plastic Surgery"), "imaging", "radiology" (or "MRI," "CT", "Advanced Imaging"). Using these terms, we systematically searched the online databases of PubMed (MEDLINE), Cochrane Library, ScienceDirect, Scopus, Google Scholar, ProQuest, and Web Of Science up to August 2023. The records from the different databases were compiled in a comma-separated values (CSV) file on Google Sheets.

2.2. Preliminary Screening

We excluded non-English articles and study types such as conference abstracts, commentary, and duplicate papers with the same digital object identifier (DOI) using a script written in the Python programming language (Python Software Foundation, Wilmington, DE, version 3.12.2). The selected manuscripts were then stored in the CSV for eligibility assessment and included information on authors, title, date of publication, journal, and DOI.

2.3. Eligibility Assessment

The four reviewers (BD, NK, JM, and MR) screened every article in the CSV for accuracy and best fit. We included full-text English articles, studies involving animal or human subjects, and clinical trials. After multiple rounds of screening, 76 studies were included in our review. The selected studies discussed the basic principles, development, and applications of the role of advanced imaging in facial reconstructive surgery.

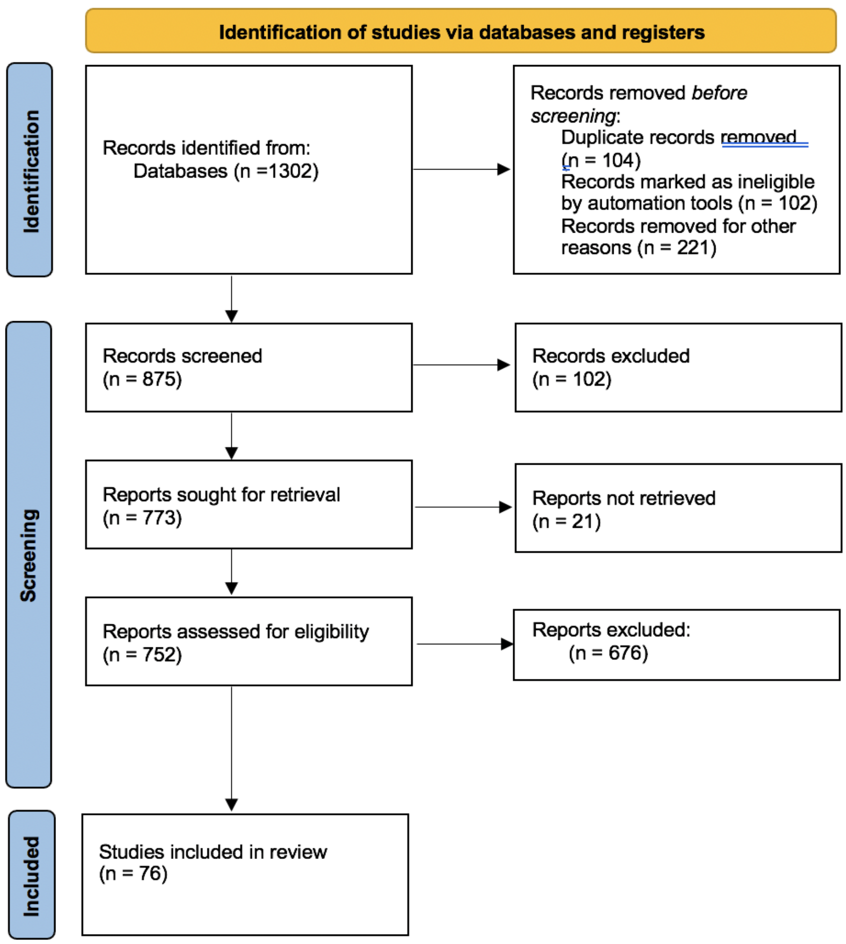

Figure 1: PRISMA Flowsheet Showing Initial Search, Screening, and Total Articles Included

2.4. Preoperative Planning

Careful preoperative planning of facial reconstructive surgery is necessary for enhanced patient outcomes, both in regards to avoiding complications and ensuring surgical intervention is successful and efficient. A primary component of preoperative planning is radiographic imaging, which provides a guide for surgical intervention, accurate and efficient transplantation, and a confirmation of dysmorphic pathology for which the surgery is indicated [3]. Radiographic imaging thus allows the surgeon to visualize the spatial field on which they will operate, which in the realm of facial reconstructive surgery, is anatomically intricate and requires precise preoperative planning. It should be noted that while individual imaging modalities can elucidate extensive information, a multimodal approach often yields the most comprehensive data preoperatively [4].

Radiologic intervention prior to facial reconstruction provides a blueprint for precise and efficient surgical intervention. CT scan measurements permit a quantitative assessment of the cranio-orbito-zygomatic skeleton in both the horizontal and transverse planes, allowing for more accurate analysis of the bony skeleton which confirms clinical findings [5]. Additionally, CT scans can be integrated with computer-aided design and manufacturing (CAD/CAM) programs to prefabricate bone plates for osteosynthesis, manufacture surgical guide templates for osteotomies, and produce 3D models for simulation surgery, allowing for a careful understanding of each case before surgical intervention. One study demonstrated that combining a preoperative CAD/CAM method and a navigation system to generate free navigation reference points (FNRPs) for assisting secondary zygoma reduction is accurate and practical. Such a navigation system is especially important for precisely locating screw holes and highlights the utility of CT-based CAD/CAM in planning [6]. Additionally, the advent of 3D printing based on CT imaging has shown value in preoperative planning. One can consider aesthetic facial bone surgery, in which alteration of mandibular angles has not been very easily attained. One study depicted that 3D-printed surgical guides made this alteration feasible, bridging the gap between simulation and actual surgery [7]. Proper implementation of radiographic imaging can thus provide detailed simulated guides for a seamless surgical intervention.

In addition to providing a blueprint for facial reconstruction, radiologic intervention aids in identifying the most appropriate donor grafts to be used for transplantation procedures [8]. Three dimensional cephalometric analyses along with advanced computer planning offers the opportunity to obtain precise facial measurements, such as facial proportions and angles, to determine the most appropriate donor-recipient match prior to surgery [9]. Furthermore, the virtual environment of advanced radiologic intervention allows for extensive non-invasive experimentation that aids in determining surgical design, such as optimal alloflap design and inset, in order to achieve the best transplantation results [9]. The ability of radiologic imaging software to obtain and store donor cephalometric values is invaluable to preoperative planning. Donors and recipients can be identified and matched based on their anthropometric similarities prior to surgery, reducing the overall ischemic time of donated tissue as well as the transplant-shaping time during surgery [9-13]. As a result, radiologic intervention allows for a quicker, more accurate, and less invasive way of planning transplantation procedures.

2.5. Postoperative Confirmation of Accuracy

As radiology's use in preoperative planning offers many advantages, its implementation as a postoperative technique has been shown to be beneficial in identifying and quantifying skeletal changes associated with reconstructive surgery. Postoperatively, multiple factors may weigh into selecting radiographic procedures for a particular case, including cost, availability, radiation exposure, and a patient's anatomy. With the many advancements in digital technology, computer-aided design and rapid prototype manufacturing techniques have become more prevalent in meeting the primary goals of reconstructive surgery.

Its use in postoperative workflows helps improve surgical accuracy by measuring skeletal manipulations or soft tissue augmentations through CAD/CAM. These changes are then compared through the systematic use of postoperative scanning with preoperative CAD to analyze bony shifts following surgical treatment [14]. In addition to computer-aided designs and templates, static and dynamic MRIs have been employed to evaluate joint movement in a study characterizing joint dysfunction disorders [15]. Specifically, dynamic MRIs offer the ability to pursue accurate image acquisition in a non-invasive manner for better visualization of anatomy and avoid radiation hazards associated with CT. Moreover, MRIs can provide a timeline of acute and chronic changes that explore arthritic deformities, evaluating the safety and efficacy of intra-articular interventions [16].

Regarding the postoperative timeline, different types of radiography may be optimal during this time. In one such study, plane radiography was primarily used to evaluate new bone growth during the early stages. In contrast, 3D CT may obtain a more robust resolution in long-term outcomes [17]. In a study featuring cross-gender cadaveric facial transplantation, skeletal proportions and facial-aesthetic were further successfully harmonized as the transplants were found to be equivalent to all reported experimental/clinical gender-matched cases by using 3D cephalometric analyses rendering posttransplantation imaging [9]. To achieve acceptable hybrid skeletal harmony, the study elucidated the success of gender-mismatched transplantation. Post-surgical imaging can be seen as a potent indicator of surgical efficacy and clinically-defined improvement of patient outcomes.

Another use of imaging postoperatively that showcases its vitality is identifying implant replacements and removals. Following radiographic imaging, implants may be replaced or removed immediately if local infection or loosening should occur. Defects with surgical construction of implants can also be remediated following visualization [18]. Tomographical imaging in the postoperative phase can evaluate any long-term changes in the implant's fixed position and function and evaluate the implant's status and prognosis. Due to the risk of intraoperative contamination and implant incompatibility, following a placement using radiography is of utmost importance and salient for the success of prosthetic rehabilitation. Post-surgical imaging also serves a dual purpose of routinely investigating the local bone structure with the bony structures directly adjacent to the implant to note any changes in mineralization or bone volume. In another study consisting of patients with nasal bone fractures who underwent augmented rhinoplasty, facial 3D CTs were used to reduce misdiagnosis and implant failure rate. Therefore, radiographic support in a postoperative setting can be imperative to maintaining successful implantation [19-22].

2.6. Cone-Beam Computed Tomography (Cbct) Allowing For 3d Facial Model Reconstruction And 3d Cephalometric Measurement

Cone-beam computed tomography (CBCT) is a valuable imaging technique that has become increasingly important in treatment planning and diagnosis in multiple procedural and surgical fields. The technique involves the use of x-ray computer tomography, where the x-rays are divergent and form a cone to produce a digital volume. The digital volume is composed of 3D anatomical voxels that can be visualized and manipulated with the specialized software [23].

CBCT is valuable in determining the most suitable approach for facial reconstructive surgery. In the setting of a rhinoplasty, CBCT can be used as a roadmap for the surgical procedure as it allows the surgeon to analyze the facial structures of the patient both prior to and during surgery [24]. With CBCT, the surgeon can study the septum in progression, evaluate the inferior and middle turbinates, analyze the sinuses and ostiomeatal drainage, assess nasal bone features, and three-dimensionally visualize the facial skeleton, among other advantages [24]. CBCT offers detailed visualization of the bony and soft tissue structures of the face as well as of air, making this imaging method an invaluable radiological technique for facial reconstructive surgery [25]. When considering dental remodeling in facial reconstructive surgery, CBCT images are especially advantageous for preoperative imaging of alveolar cleft morphology. This is due to the high degree of accuracy of CBCT linear measurements in relation to anatomy as well as its reliability in volumetric assessment of alveolar cleft defects [26].

In addition to its preoperative advantages, CBCT allows for an accurate evaluation of postoperative facial structures. As such, 3D skeletal and soft tissue changes can be evaluated for as much as one year after reconstructive procedures such as a mandibular advancement [27]. Correlations between mandibular advancement and volumetric changes of the hard tissues can be delineated due to CBCT's utility in documenting volumetric surgical changes accurately and objectively. The multidimensional nature of CBCT allows it to be a valuable reproducible tool for the 3D rendering of facial structures, allowing longitudinal follow-up and quantitative analysis following surgery [28]. Similarly, this novel technique has also been shown to conceptualize microstructural features of regenerated bone tissue, which enables direct comparison with the presence/absence of artificial bone material and the features of regenerated bone tissue [29]. In clinical practice, CBCT's ability to display volumetric, multiplanar reconstructions has demonstrated an advantage for postoperative outcomes.

Compared to conventional CT radiography, CBCT has been shown to require less radiation, which is especially beneficial to patients undergoing multiple preoperative and postoperative tomography. CBCT requires less radiation exposure and offers skull imaging with high geometric accuracy in all spatial planes and 3D reconstruction at high resolution [30]. It has been recommended as the ideal imaging technique in orthognathic surgery, as it uses ultra-low-dose CT imaging of maxillofacial fractures. However, CBCT does pose certain disadvantages that must be considered, such as its low contrast range, restricted field of view, reduced scanned volume caused by limited detector size, and increased noise from scatter radiation and artifacts [31]. Despite its drawbacks, CBCT possesses several advantages over medical CT in clinical practice, such as its use for preoperative planning and postoperative control, lower effective radiation doses, lower costs, and easier image acquisition, making it an ideal candidate for facial reconstructive radiography.

2.7. Diagnosis of Fracture Following Facial Surgery (e.g., Augmented Rhinoplasty)

Facial reconstructive surgery has been not only instrumental in cosmetic surgery but also in the evaluation and treatment of craniofacial fractures; thus, it is important for the surgeon to have a keen understanding of the precise fracture prior to, during, and following surgery.

As noted previously, CT has shown to be the leading modality in radiographic examination of facial skeleton deformity [32-51]. Following an orbital wall fracture, CT imaging provides key information regarding orbital volume changes for preoperative and postoperative evaluations [52]. In cases of blowout fractures, CT allows for complicated volume measurements to be obtained [53, 54]. Furthermore, CT provides useful information regarding bony regeneration by measuring bony calcifications at the end of the fracture and its contour, as it is useful in analyzing both bone intensity and density [55]. CT imaging can furthermore be used as a predictor of pathology. Particularly, identification of nasolacrimal system (NLS) fractures on CT can assist surgeons in determining which patients will develop lacrimal outflow obstruction symptoms and eventually need lacrimal surgery [56].

While CT provides very useful information in evaluating fractures, other modalities also provide pertinent information. Active transport dacryocystography, for example, seems an appropriate diagnostic technique in evaluation of the LDS after rhinoplasty or after midfacial fractures [57]. Additionally, ultrasonography is an effective screening and intraoperative tool in facial reconstructive surgery as it can be used to assess zygomatic complex fractures while avoiding unnecessary incisions in aesthetic areas of the maxillofacial region [58-64].

2.8. Computed Tomography Angiography in Determining Location of Head and Neck Bleeding

Computed tomography angiography (CTA) is one modality used for preoperative planning, specifically for demonstrating the location and cause of acute massive head and neck bleeding. It combines a computerized scan with an injection of a contrasting dye to produce images of blood vessels and tissues in a particular body region [65,66]. Widespread use of CTA in emergency situations, such as blunt force trauma, has been useful to determine the source and localization of blunt cerebrovascular injuries that may require angiographic or surgical intervention. Studies have also shown that CTA has particularly been found successful in cases with continuous active extravasations and bleeding caused by pseudoaneurysms [57,67]. CTA above the supra-aortic level is usually obtained in such cases and is promptly evaluated by an experienced radiologist to determine the localization of bleeding if the patient's clinical condition permitted [67].

CTA also offers excellent noninvasive angiographic imaging modality of facial vascular lesions. As blunt force trauma can lead to major facial deformities, plastic surgeons can benefit from incorporating angiography exams in their patient evaluation to thoroughly assess the level of facial malformation. The 3D CTA in particular, with high spatial and temporal resolution, proved to provide distinct features that enabled excellent lesion detection, characterization, visualization of feeding arteries and draining veins and complete extensions [68]. 3D CTA also allowed accurate differentiation of hemangiomas from arteriovenous malformations that is sometimes difficult using clinical examination and 2D CTA [68]. The 3D CTA plays an important role in extension evaluation, treatment planning, and follow up, thus eliminating the need for invasive digital subtraction angiography.

In addition, head and neck bleeds can be identified as a consequence of certain anastomoses following flap reconstruction. Consequences of flap reconstruction can affect the scalp, skull base, mandible, and midface, such as the orbit. Fine-cut CT scans and volumetric 3D reconstruction are necessary to delineate and measure the abnormality in orbital volume [69]. Information obtained from these imaging modalities are essential for the surgeon during reconstruction in order to predict the size of the bone graft to use, as well as to determine the ideal location of its placement.

2.9. Radiologic Imaging in Primary Site Surveillance in Head and Neck Cancer (Hnc)

The unique ability of radiologic imaging to identify and visualize head and neck tumor masses makes it an invaluable diagnostic tool. Diagnostic imaging of tumor masses is achieved through three methods: 1) confirming the presence of a tumor, 2) distinguishing similar tumor tissues from one another, and 3) detecting unusual tumors. In the evaluation of adenomas, contrast-enhanced MRI reduces the susceptibility artifacts from the skull base and better visualizes the density of compressed tissue, allowing for confirmation of the presence of macroadenomas involving the left cavernous sinus prior to surgery [70, 71]. Similarly, radiologic imaging such as magnetic resonance elastography (MRE) provides a method for distinguishing similar tumor tissues from one another. Through its ability to determine both tumor tissue stiffness and consistency, MRE can distinguish metastatic pituitary tumors from pituitary macroadenomas (PMAs) [72]. This is especially important when considering further classification of PMAs as MRE has been shown to be uniquely adept at both distinguishing and identifying the first case of firm PMA tumor tissue in the current literature. Finally, radiologic imaging can assist in the detection of unusual tumor masses. Metastatic melanomas can demonstrate unusual features on MRI due to the paramagnetic effect of melanin, highlighting the usefulness of MRI in the identification and diagnosis of unusual tumors. Similarly, PET/CT in combination with panendoscopy have shown promising results in increasing the detection rate of unknown primary head and neck carcinoma [42,73].

An added advantage of radiologic imaging is the ability to visualize the volume and extent of tumor tissue prior to surgery. Through virtual resection planning of preoperative images, surgeons have the improved ability to visualize resection tumor volume three dimensionally, allowing for an enhanced view of the extent of the tumor in the body [74]. The visualization of anatomic structures is incredibly valuable, especially when analyzing the patency of vessels. The Maximum Intensity Projection (MIP) technique has shown effectiveness in examining the vascular structures in question, while also providing visual evidence to rule out additional pathology, such as thrombus, compression, and displacement by the tumor [75]. These techniques are important for the HNC surgeon and can be used to aid in the decision-making process of HNC patients when considering surgery. In comparison studies between 2D and 3D SPECT/CT, 3D SPECT/CT has shown usefulness in determining the treatment strategy for jaw bone invasion (JBI), while also offering a way to visually explain the details of jaw surgery to patients and convincing them of its necessity [76].

Finally, radiologic imaging is an asset when visualizing the resection margins during and after HNC surgery. In acromegalic patients, the combination of extra-pseudocapsule resection and endoscopy has led to a high rate of gross total tumor resection as well as endocrinological remission compared to groups with intracapsular resection [71]. The ability for enhanced visualization, planning, and evaluation of HNC both pre and post-resection makes radiologic imaging an invaluable tool for primary site surveillance of HNC.

2.10. Imaging Modalities Used in Diagnosis of Nerve Lesions (e.g., DCE-MRI in Facial Nerve Lesions)

Imaging plays a critical role in the evaluation of a number of facial nerve disorders commonly seen by plastic surgeons. Because of the significant associated morbidity, prediction of facial nerve sacrifice is critically important for planning surgical procedures and preoperative counseling of patients. The facial nerve has a complex anatomical course; thus, thorough imaging of the facial nerve is essential to localize the sites of pathology. Detecting the probability of sacrifice of the facial nerve during resection through radiology can be crucial for preoperative surgical planning. Both CT and MRI during this phase can help for this risk assessment, as they both have a high negative predictive value for facial nerve sacrifice [77, 78].

Although multiple scanning modalities have had varying degrees of effectiveness, MRI scanning has proved to be a feasible option in demonstrating the changes of the facial nerve. MRI visualizes soft tissues well and thus is better suited for evaluating soft tissue facial nerve abnormalities than CT. Specifically, MRI enhancement of facial nerves in specific conditions, Bell's palsy and Ramsay Hunt syndrome, is associated with the extent of intratemporal lesions of facial nerves, especially in the labyrinthine segment [79]. Swelling of facial nerve segments was found in patients with enhanced facial nerves from MRI, deeming it to be a suitable approach in diagnosing facial nerve lesions [79]. Adding on dynamic contrast-enhanced (DCE) to conventional MRI has further shown to accurately identify characteristic imaging findings of Bell's palsy particularly in involved segments [80]. Conventional MRI combined with DCE-MRI is a useful way to diagnose the involved segments of the affected facial nerves accurately with a shorter acquisition time compared to conventional MRI. This approach has advantages both for patient safety and for accuracy of the diagnosis. Compared to standard T1 weighted images in conventional MRI, DCE-MRI results in a shorter acquisition time, higher spatial resolution, and achievement of quantitative parameters [80]. The ability of DCE-MRI to accurately identify characteristic imaging findings for patients with Bell's Palsy can be transformative in its early detection and management protocol.

Additionally, newer techniques have been developed for safe deep facial tissue dissection. Many procedures require dissection of deep facial tissue where the facial nerve courses, such as tumor removal, facial paralysis reconstruction, and corrective facelifts [81]. Surrounding ligaments anatomically resemble the features of the facial nerve, often making it difficult to distinguish which tissue to incise [81]. As a solution, utilizing indocyanine green (ICG) - assisted direct visualization of the facial nerve during surgeries involving deep facial tissue dissection can help investigate the effectiveness of real-time direct visualization. Without direct visualization of the vasa nervorum of facial nerve trajectory, there is a risk of nerve injury; therefore, this technique might help to reduce the risk of complications of facial palsy. Preliminary case studies have shown that after the usage of ICG and a near-infrared camera for direct visualization, the surrounding anatomy was well maintained and facial nerve dissection was performed with positive patient outcomes [82].

Radiological imaging can aid plastic surgeons in better visualizing facial nerves by providing landmarks which help the surgeon measure the distance between certain areas. Thickness measurements obtained at various sites measured between different nerves of the face provide practical reference information for mandibular reconstruction [83]. Using radiological softwares, such as the AquariusNET Viewer, to calculate distances between certain facial nerves can assess the degree of mandibular reconstruction [83]. Knowledge of mandibular thickness measurements can be used as a practical reference for numerous applications, including mandibular fracture repair, mandibular reconstruction, and in obtaining a better understanding of mandibular anatomy [83]. Imaging can provide critical information for diagnosis and treatment of facial nerve disorders.

3. Conclusion

The field of facial reconstructive surgery is an advancing field, fueled by innovations in surgical techniques and technologies. This comprehensive review highlights the indispensable role of advanced imaging modalities in optimizing patient outcomes and surgical decision-making. Through meticulous preoperative assessment, precise intraoperative navigation, and comprehensive postoperative monitoring, advanced imaging techniques such as CT, MRI, 3D photography including CBCT, and VSP have become integral components of modern facial reconstructive practice. By providing detailed anatomical information and facilitating interdisciplinary collaboration, these imaging modalities enable surgeons to tailor individualized treatment strategies following facial fractures, determine the location of head and neck bleeding and tumors, and help in identifying levels of nerve lesions. These advantages can result in improved surgical precision, strengthened training for surgical personnel, reduced operative times, and enhanced patient satisfaction. The findings of this review highlight the importance of advanced imaging technologies in facial reconstructive surgery, with the ultimate goal of improving quality of life and outcomes for patients.

Institutional Review Board Statement

Not applicable as this is a retrospective review of published manuscripts.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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Conflict of Interest

The authors declare no financial disclosures or conflicts of interest in this work.

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