U.P.B. Sci. Bull., Series B, Vol. 87, Iss. 4, 2025 ISSN 1454-2331

3D-PRINTED ANATOMICAL REPLICAS DERIVED FROM CBCT AND CT IMAGING FOR ENDOSCOPIC SINUS SURGERY: DEVELOPMENT, ACCURACY, AND CLINICAL RELEVANCE

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The integration of three-dimensional (3D) printing into medical and dental practice has expanded rapidly, offering new opportunities for surgical training, anatomical education, treatment planning, and patient communication. This systematic review aims to synthesize interdisciplinary evidence regarding 3D-printed anatomical models derived from CBCT and CT imaging, with emphasis on their anatomical accuracy, educational value, clinical applications in ESS and dental practice, and the characteristics of polymers and composite materials used in their fabrication.

Keywords: 3D printing; CBCT; CT imaging; Surgical training; Polymer-based materials.

1. Introduction

Three-dimensional (3D) printing has transitioned from an emerging technology to a widely adopted tool across multiple medical and dental specialties. Its capacity to convert radiological datasets into accurate, patient-specific anatomical replicas has considerably influenced surgical planning, clinical education, and simulation-based training. In recent years, significant progress has been made in otorhinolaryngology (ENT), where 3D-printed models have been successfully used in otologic surgery, skull base approaches, and functional endoscopic sinus surgery (FESS) to enhance training quality and overcome the increasing limitations associated with cadaver procurement [5–7]. Notably, temporal bone models printed from high-resolution CT scans have demonstrated excellent anatomical fidelity and realistic drilling characteristics, supporting their integration into standardized training curricula [5,8–10].

Parallel developments have occurred in dentistry, where cone-beam computed tomography (CBCT) is widely used for diagnostic purposes and

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treatment planning. Due to its lower radiation dose, accessibility, and high spatial resolution in the dentoalveolar region, CBCT has become a common imaging source for generating 3D-printed models used in implantology, maxillofacial surgery, and educational settings [1,11]. Studies have demonstrated that CBCT-derived replicas offer reliable dimensional accuracy for preoperative planning and hands-on training, often matching or exceeding the performance of traditional cast models [1,11,14]. Furthermore, CBCT-based assessments of bone quality and mandibular indices are clinically relevant, particularly in evaluating patients with low bone mass [15–17], thereby reinforcing the utility of this imaging modality in interdisciplinary applications.

The choice of printing material represents another critical component in creating anatomically and functionally accurate models. Polymerized resins, photopolymer composites, and polylactic acid (PLA) are among the most frequently used materials, each offering specific advantages in terms of biocompatibility, structural rigidity, and haptic realism [1,6,10,12]. In addition, recent technological advances have enabled the development of multi-material printing techniques, facilitating the production of complex structures that incorporate both soft-tissue-like and bone-like components within the same model [13]. Beyond training applications, innovative uses have been documented, including the development of 3D-printed PLA sinus stents loaded with corticosteroids to enhance postoperative healing in chronic rhinosinusitis [18], which highlights the expanding translational potential of 3D printing in rhinology.

Despite these advancements, evidence remains heterogeneous across fields regarding optimal imaging workflows, segmentation processes, material selection, and the relative advantages of CBCT versus conventional CT. CT remains the gold standard for replicating intricate sinonasal and skull base anatomy due to its superior soft-tissue and bone detail [5, 8, 9]. In contrast, CBCT offers an accessible and workflow-efficient alternative for printing models of the nasal fossae, maxillary sinus, and dentoalveolar structures [11,14]. Given the parallel evolution of 3D printing in ear, nose, and throat (ENT) surgery, dentistry, and materials science, a comprehensive synthesis of interdisciplinary evidence is essential. To date, most publications have focused on single-specialty applications, without systematically contrasting how CT- and CBCT-derived 3D-printed models are used, validated, and limited across ENT and dental/maxillofacial practice.

Therefore, this systematic review aims to integrate current research on 3D-printed anatomical models derived from CBCT and CT imaging, with emphasis on their anatomical accuracy, clinical applications in endoscopic sinus surgery and dental practice, educational value, and the performance of polymer-based materials used for model fabrication. By bringing together ENT, dental, and polymer science perspectives, the review provides a structured framework for understanding when CT-based models are required, when CBCT-based replicas are sufficient, and how material selection affects the realism and pedagogical utility of 3D-printed anatomical replicas [23].

2. Materials and Methods

A systematic literature search was conducted in PubMed and Web of Science to identify studies describing the creation, validation, or use of three-dimensional (3D) printed anatomical models derived from cone-beam computed tomography (CBCT) or conventional computed tomography (CT). The search strategy combined controlled vocabulary and free-text terms related to 3D-printed anatomical replicas, imaging modalities, endoscopic sinus surgery (ESS), surgical training models, and polymer-based printing materials. The reference lists of the included articles were also screened to ensure that relevant studies were not overlooked. Only peer-reviewed publications written in English were considered eligible.

For the database screening, the following filters were applied: “English language,” “full-text available,” “human studies,” and document type restricted to “original research articles.” Additional filters were applied where available to exclude conference abstracts, reviews, book chapters, and non-peer-reviewed sources. The selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles, which included several steps. These steps began with the removal of duplicates and continued with title and abstract screening to evaluate relevance. Full-text articles were retrieved when abstracts did not provide sufficient information or when eligibility remained uncertain.

Original studies were included if they met the following criteria:

- Described the fabrication of 3D-printed anatomical models from CBCT or CT datasets;
- Reported dimensional, anatomical, clinical, educational, or material-related validation outcomes;
- Involved anatomical regions relevant to otorhinolaryngology (ear, nose, and throat – ENT), dentistry, maxillofacial surgery, or biomaterials science;
- Provided sufficient methodological detail to allow assessment of imaging parameters or printing workflows.

Exclusion criteria were:

- Studies not involving 3D-printed anatomical models;
- Studies using imaging modalities other than CT or CBCT;
- Review articles, editorials, opinion papers, letters, conference abstracts, and book chapters;

- Articles lacking extractable methodological information or accurate data.

The literature search, carried out between January 1, 2020, and December 31, 2024, identified 385 records in PubMed and Web of Science (218 from PubMed and 167 from Web of Science). Following the removal of 71 duplicates, 314 unique records were screened by title and abstract, resulting in the exclusion of 241 studies that did not meet the predefined criteria. The remaining 70 articles underwent full-text evaluation, after which 22 were excluded due to insufficient methodological detail or lack of relevance. In total, 48 studies met all eligibility criteria and were included in the qualitative synthesis.

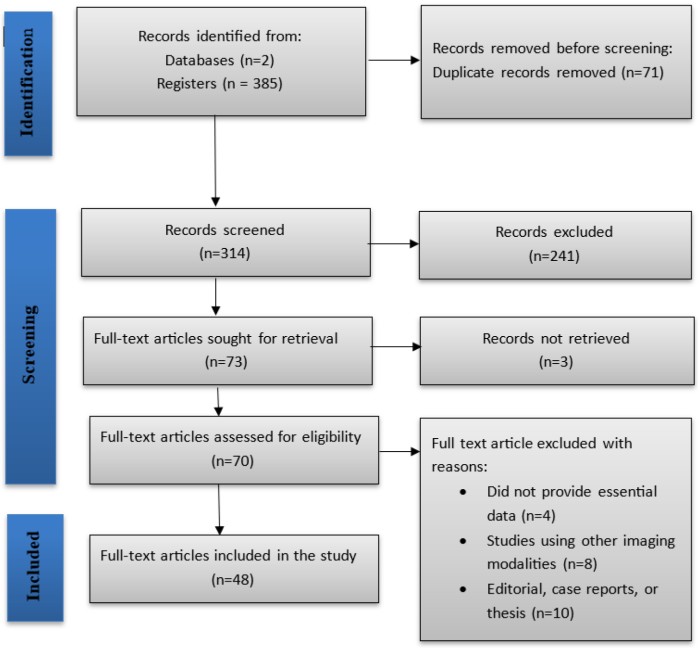

Fig. 1. The flow chart of the article selection process

Data extraction was performed manually, focusing on key elements reported within each study. These included the imaging modality used for model generation, the anatomical region of interest, the segmentation workflow, the characteristics of the printing materials, the reported accuracy or validation outcomes, and the clinical or educational purpose of the model.

Given the significant methodological heterogeneity between studies—particularly regarding imaging parameters, anatomical targets, segmentation protocols, printing technologies, and outcome measures—a meta-analysis was not feasible. Therefore, a narrative synthesis approach was adopted to integrate findings across ENT, dental, and biomaterials domains.

Methodological quality was assessed descriptively, considering the clarity of the imaging acquisition parameters, the transparency and reproducibility of the segmentation and printing processes, and the extent to which the anatomical accuracy of the models was validated. The relevance of each study to clinical practice, surgical training, or material science was also taken into account. Because the included studies ranged from technical engineering analyses to clinical education research, a unified risk-of-bias assessment tool was not applicable.

3. Results

3.1. Applications in Otorhinolaryngology (ENT)

The use of three-dimensional (3D) printed anatomical models has expanded significantly within otorhinolaryngology, particularly in subspecialties that require a detailed understanding of complex bony structures, such as otology, skull base surgery, and functional endoscopic sinus surgery (FESS). Temporal bone surgery represents one of the earliest and most extensively documented applications, where 3D-printed replicas based on high-resolution CT data have enabled surgeons and trainees to rehearse drilling techniques in a controlled and reproducible environment. Studies have shown that these models accurately reproduce essential anatomical landmarks and provide a realistic tactile experience during drilling, with reported resemblance rates exceeding 85% when compared to cadaveric specimens [5,8–10]. This fidelity has supported their integration into training programs and multi-institutional comparisons, confirming their suitability for standardized surgical education [9,10].

Beyond otology, the adoption of 3D printing has grown within rhinology and skull base surgery. Advances in endoscopic approaches and the growing need for structured training have encouraged the development of sinonasal and skull base models derived from CT imaging. These models have been used to practice fundamental steps of FESS, including middle meatus antrostomy, ethmoidectomy, and sphenoidotomy, and have demonstrated utility in improving trainee confidence and technical performance [5,7]. In particular, models created from CT scans offer a detailed representation of the ethmoid labyrinth, sphenoid sinus, and skull base, which remain critical areas for developing surgical competence and spatial orientation.

In more recent work, 3D-printed sinonasal models have been validated for use in simulation-based training for both standard and advanced endoscopic procedures. Residents consistently report improved understanding of anatomical relationships and greater comfort performing endoscopic manoeuvres after training on printed models, which provide hands-on experience without the ethical and regulatory challenges associated with cadaveric dissection [7]. For patient-specific simulations, CT-based models have been used to illustrate anatomical variations, explain procedural steps, and enhance patient understanding of surgical planning, contributing to improved communication and adherence to treatment [13,14].

Collectively, the evidence supports a growing role for 3D-printed models in ENT surgical training and clinical communication. CT remains the preferred imaging modality for advanced sinonasal and skull base applications. At the same time, CBCT serves as an accessible, lower-radiation alternative for targeted anatomical regions and for integrating ENT and dental training scenarios. However, CBCT demonstrates well-recognized limitations in ENT applications, including reduced soft-tissue contrast, smaller field-of-view options, and susceptibility to scattering and metallic artefacts, which may compromise the accurate reproduction of ethmoid and sphenoid structures. These constraints restrict its use primarily to anterior sinonasal training and maxillary sinus simulations. Additionally, CT typically provides more stable grayscale calibration, enabling higher-fidelity segmentation for complex bony regions. In contrast, CBCT's dose efficiency and accessibility remain its main advantages in early-stage and interdisciplinary ENT–dental scenarios [24].

Table 1

Overview of ENT applications of 3D-printed anatomical models and associated imaging modalities.

Clinical Area (ENT)	Purpose of the 3D-Printed Model	Imaging Modality Used	Key Points Reported in the Literature
Temporal bone surgery	**Surgical drilling training; anatomical orientation; preoperative planning**	**CT**	**High anatomical fidelity; realistic drilling feedback; validated across institutions [5,8–10].**
Functional endoscopic sinus surgery (FESS)	**Simulation of ethmoidectomy, sphenoidotomy, antrostomy**	**CT**	**Best for complex sinonasal anatomy; necessary for superior detail in the ethmoid and sphenoid regions [5,7,9].**
Basic endoscopic sinus training (nasal cavity, maxillary sinus)	**Early-stage FESS training; procedural rehearsal**	**CBCT**	**Adequate for nasal fossae and maxillary sinus; accurate linear/volumetric reproduction [11,14].**
Skull base endoscopic approaches	**Simulation of advanced extended endoscopic techniques**	**CT**	**Enables practice of delicate maneuvers; supports interdisciplinary neurosurgical–ENT training [5].**
Patient education and communication	**Explaining anatomical variations; reviewing surgical steps**	**CT or CBCT**	**Enhances patient understanding; improves informed consent process [13,14].**

Note: *CT = computed tomography; CBCT = cone-beam computed tomography. The table summarizes the key clinical applications of 3D-printed models in otorhinolaryngology, as well as the imaging methods used in the literature.*

3.2. Dental and Maxillofacial Applications

The integration of 3D-printed anatomical models into dental and maxillofacial practice has expanded considerably in recent years, primarily driven by the widespread adoption of cone-beam computed tomography (CBCT). CBCT has become the principal imaging modality in dentistry due to its ability to generate high-resolution volumetric datasets of the maxillofacial complex while maintaining a lower radiation dose compared with conventional CT. These datasets have been increasingly used to fabricate 3D-printed models that support diagnostic processes, treatment planning, surgical rehearsal, and the development of clinical skills among trainees.

Several studies have demonstrated that CBCT-derived 3D-printed models offer reliable dimensional accuracy for a wide range of dental applications. Such models have been used in implantology, orthodontics, and restorative dentistry to evaluate anatomical relationships, assess bone volume, and preoperatively plan surgical interventions with high precision [1,11]. In orthodontics and maxillofacial surgery, printed models based on CBCT have shown accuracy comparable to traditional cast models while providing superior visualization of complex structures and spatial relationships [11]. Their reproducibility and ease of fabrication make them particularly valuable in educational settings, where they allow trainees to practice complex procedures without patient-related risks.

The use of 3D-printed models is particularly beneficial in cases that require a detailed assessment of bone quality and morphology. CBCT-based measurements of mandibular indices have become increasingly important in evaluating patients with primary or secondary low bone mass, conditions that can significantly impact implant stability and surgical outcomes [15–17]. Studies evaluating mandibular cortical indices, panoramic mandibular indices, and other CBCT-derived parameters have shown strong correlation with bone density assessments, highlighting the role of CBCT as a clinically relevant tool in both diagnosis and preoperative planning. These imaging datasets, when translated into 3D-printed replicas, can further support decision-making in complex implant cases or reconstructive procedures.

Beyond bone-related applications, CBCT-based 3D printing has been used to simulate maxillary sinus anatomy in cases involving odontogenic sinusitis, sinus floor elevation, or transcrestal approaches, facilitating risk assessment and procedural planning. Printed models allow clinicians to visualize sinus septa, mucosal thickening, and the relationship between dental roots and the sinus floor, supporting both surgical safety and patient education [11,14].

The educational value of 3D-printed models in dentistry is well-documented. Training programs have incorporated CBCT-derived replicas to provide students and residents with hands-on experience in techniques such as implant placement, osteotomy preparation, and surgical flap management. These models provide a safe, reproducible, and cost-effective learning environment, which has been shown to enhance procedural confidence and reduce the learning curve for young clinicians [1]. Moreover, the combination of CBCT imaging and 3D printing has facilitated innovative research directions, particularly in the development of biomaterials and drug-delivery systems. For example, polylactic acid (PLA), widely used in dentistry and biomedical engineering, has been incorporated into 3D-printed constructs capable of supporting local drug release, representing a promising translational application that further connects dental imaging, materials science, and clinical practice [12,18].

Table 2

Dental and maxillofacial applications of 3D-printed anatomical models derived from CBCT imaging.

Clinical Area (Dental/Maxillofacial)	Purpose of the 3D-Printed Model	Imaging Modality Used	Key Points Reported in the Literature
Implantology and oral surgery	**Preoperative implant planning; assessment of bone volume and morphology; surgical rehearsal**	CBCT	**High dimensional accuracy for dentoalveolar structures; supports surgical safety and reduces intraoperative uncertainty [1,11].**
Orthodontics and maxillofacial analysis	**Evaluation of craniofacial relationships; planning of orthodontic movements and corrective osteotomies**	CBCT	**Reliable reproduction of anatomical landmarks; comparable or superior to cast models for complex measurements [11].**
Assessment of bone quality in low bone mass conditions	**Evaluation of cortical thickness, mandibular indices, and bone morphology**	CBCT	**Strong correlation between CBCT-derived indices and bone density; clinically valuable in diagnostic workflows [15–17].**
Maxillary sinus anatomy (odontogenic sinusitis, sinus lift planning)	**Visualization of sinus floor, septa, and relations with dental roots**	CBCT	**Accurate linear and volumetric measurements; suitable for interdisciplinary ENT–dental planning [11,14].**
Educational and training applications	**Implant placement drills; osteotomy simulations; skill development for trainees**	CBCT	**Safe, reproducible, cost-effective environment; improves trainee confidence and procedural understanding [1].**

Note: CBCT = cone-beam computed tomography. The table summarizes major dental and maxillofacial applications of CBCT-derived 3D-printed anatomical models reported in the literature.

In dental applications, CBCT datasets generally provide sufficient contrast for highly accurate printed replicas [25].

3.3. Materials and Polymer Characteristics

A wide variety of materials have been employed in the fabrication of 3D-printed anatomical models used in ENT, dental, and maxillofacial applications, each selected for its ability to replicate specific structural, tactile, or biomechanical properties. Polymer-based materials remain the predominant choice across fields, owing to their accessibility, biocompatibility, dimensional stability, and adaptability to different printing technologies.

Photopolymer resins are widely used in medical 3D printing due to their ability to reproduce fine anatomical details with high precision. These materials are commonly selected for ENT applications, especially when replicating complex sinonasal or temporal bone anatomy, where structural accuracy is essential for surgical training or preoperative planning [5–7]. Resin-based models generated from CT data have demonstrated excellent anatomical fidelity in temporal bone simulations, closely mimicking both the cortical and trabecular bone patterns encountered during drilling [6,8–10]. The hardness and brittleness of these photopolymers contribute to a realistic haptic sensation during dissection, which has supported their integration into standardized training programs [9].

Composite materials have also gained traction due to their versatility and capacity to mimic multiple tissue types within a single print. Specific composite formulations incorporate fillers or additives, such as chalk powder, to enhance drilling resistance and improve similarity to natural bone. These modifications have demonstrated superior tactile realism compared with conventional resins and have been successfully applied in otologic and skull base training models [6,10]. More advanced systems enable printing with variable hardness, allowing the reproduction of structures with differing mechanical properties, such as soft–tissue–like regions and rigid osseous components, within the same anatomical model. This capability is particularly relevant for intricate surgical procedures that require differentiation of tissue planes, and it has shown considerable promise in simulating endoscopic skull base surgery [13].

In dentistry, the material landscape also includes acrylate-based resins, such as polymethylmethacrylate (PMMA) and polyethyl- or polybutyl-methacrylate (PEMA), as well as composite resins, including urethane dimethacrylate (UDMA) and bisphenol A-glycidyl dimethacrylate (Bis-GMA). These materials are valued for their dimensional stability, smooth surface finish, and suitability for tasks that require the accurate replication of dentoalveolar anatomy [1,12]. Due to their biocompatibility and favorable handling characteristics, they are commonly used for diagnostic casts, implant planning, crown and bridge simulations, and a wide range of restorative procedures. Their intrinsic mechanical properties make them appropriate for training scenarios involving drilling, osteotomy preparation, or implant placement.

Polylactic acid (PLA), a biodegradable thermoplastic derived from renewable resources, represents another widely used material with extensive interdisciplinary applications. PLA is favored for its ease of extrusion, low cost, and capacity to produce structurally consistent models, making it suitable for both dental and ENT-related prints [12,14]. In addition to its utility in anatomical modeling,

The evolution of printing technologies has further expanded the potential of polymeric materials. Multi-head and multi-material printers now enable the combination of photopolymers, elastomers, and rigid composites within a single model, allowing for the creation of hybrid structures that more accurately simulate the biomechanical heterogeneity of human tissues. These innovations provide improved tactile feedback, enhanced anatomical realism, and new opportunities for personalized simulation across ENT and dental disciplines. In ENT applications, resin-based materials paired with CT datasets enable the high-detail reconstruction of thin bony lamellae, whereas CBCT-derived models—although sufficiently detailed for maxillofacial regions—may exhibit reduced segmentation accuracy for ultra-fine structures, thereby influencing printing fidelity. In summary, polymer and composite materials form the foundation of current medical 3D printing practice. Their ongoing refinement, together with advances in printer technology, continues to enhance the fidelity, functionality, and translational potential of anatomical models used in both clinical and educational settings.

Table 3

Common materials used for 3D-printed anatomical models and their main characteristics in ENT and dental applications.

Material Type	Representative Materials	Applications in ENT / Dental Fields	Key Characteristics Reported in the Literature
Photopolymer resins	**Standard photopolymers; surgical-grade resins**	**Temporal bone models; sinonasal and skull-base replicas**	**High anatomical fidelity; good reproduction of fine bony structures; rigid texture suitable for drilling; widely used in otologic training [5–10].**
Composite materials	**Resin–chalk composites; hybrid photopolymers**	**Otologic and skull-base drilling simulation; complex mixed-tissue models**	**Enhanced drilling realism; improved hardness and tactile properties; ability to vary stiffness within the same print; supports multi-material fabrication [6,10,13].**
Acrylic-based resins	**PMMA; PEMA**	**Dental models; restorative and prosthetic simulations**	**High dimensional stability; smooth surface finish; commonly used in prosthetic and restorative training; good optical properties [1,12].**

Composite dental resins	**UDMA; Bis-GMA**	**Dental surgical planning; implantology; orthodontic simulation**	**Excellent fine-detail resolution; suitable for drills, osteotomy preparation, and educational models; compatible with high-precision printers [1,12].**
Polylactic acid (PLA)	**Standard PLA; PLA with active pharmaceutical ingredients**	**ENT and dental anatomical models; experimental sinus stents**	**Biodegradable and versatile; easy extrusion; cost-effective; used for anatomically accurate models and drug-eluting devices in rhinology [12,14,18].**
Multi-material constructs	**Combinations of rigid and flexible polymers**	**Advanced ENT models; skull-base and sinus surgery simulation**	**Allow simultaneous printing of soft- and hard-tissue analogs; create more realistic, heterogeneous anatomical structures [13].**

Note: PMMA = polymethylmethacrylate; PEMA = polyethyl- or polybutyl-methacrylate; UDMA = urethane dimethacrylate; Bis-GMA = bisphenol A-glycidyl dimethacrylate; PLA = polylactic acid. The table summarizes commonly reported materials used in 3D-printed anatomical models in ENT, dental, and interdisciplinary applications.

3.4. Imaging Modalities: CBCT vs CT — Comparative Synthesis

Cone-beam computed tomography (CBCT) and conventional computed tomography (CT) are the primary imaging modalities used to generate three-dimensional (3D) printed anatomical models across the fields of ENT and dentistry. Although both methods are capable of producing high-resolution volumetric datasets suitable for segmentation and printing, their technical characteristics, clinical applicability, and anatomical accuracy differ significantly depending on the region of interest.

Conventional CT remains the reference standard in otorhinolaryngology for replicating complex sinonasal and skull base anatomy. Its superior contrast resolution, consistent grayscale calibration, and ability to visualize delicate bony and soft-tissue structures make it particularly suitable for printing models used in advanced endoscopic sinus surgery (ESS), ethmoid and sphenoid dissection, and skull base approaches [5, 8, 9]. CT-derived models have demonstrated high internal fidelity when compared with cadaveric specimens and have been validated across multiple institutions, confirming their suitability for enhancing surgical training and maintaining reproducibility in procedural simulation [9,10]. Temporal bone models based on CT scans remain among the most accurate printed structures, providing a realistic drilling sensation and detailed anatomical replication that are essential for training in otologic and neurotologic procedures [6,8–10].

In contrast, CBCT has become the predominant imaging modality in dentistry due to its lower radiation dose, cost efficiency, and capability to generate high-resolution images of the dentoalveolar complex. CBCT datasets are widely used to fabricate 3D-printed models for implantology, orthodontics, and maxillofacial surgery, where they have demonstrated high dimensional accuracy and consistent correlation with in vivo measurements [1,11]. CBCT is also valuable in assessing bone quantity and quality, an essential aspect of preoperative planning in patients with low bone mass or complex implant requirements. Several studies have confirmed the reliability of CBCT-derived indices in evaluating cortical thickness and mandibular morphology, supporting their use in diagnostic workflows and in the fabrication of anatomically accurate printed models [15–17].

When applied to ENT, the utility of CBCT is more selective. While it lacks the soft-tissue resolution and grayscale calibration necessary to reproduce the intricate structures of the ethmoid labyrinth or sphenoid sinus, CBCT provides sufficient anatomical information for the nasal fossae and maxillary sinus. From a radiation-dose perspective, CBCT typically exposes patients to substantially lower doses than CT, a notable advantage for dental and repeated imaging scenarios. Cost differences follow a similar pattern: CBCT units are less expensive to operate and maintain, making them more accessible in outpatient dental settings. However, CT scanners provide more consistent voxel calibration and higher contrast resolution, which are essential for ENT skull base models requiring precise delineation of thin bony partitions.

Overall, both CT and CBCT play complementary roles in the production of 3D-printed models. Their combined use supports a broad spectrum of clinical, educational, and research applications, reflecting the increasingly interdisciplinary nature of additive manufacturing in the medical field.

3.5. Summary of Findings

Across the reviewed literature, 3D-printed anatomical models generated from CT and CBCT datasets demonstrate substantial value in both ENT and dental practice. In otorhinolaryngology, CT-based models provide the level of anatomical detail required for advanced simulation in temporal bone surgery, endoscopic sinus surgery, and skull base interventions. These models reliably replicate complex osseous structures and offer realistic haptic feedback during drilling, supporting their integration into structured surgical training programs [5–10]. Within rhinology, CT remains essential for reproducing the intricate architecture of the ethmoid and sphenoid regions. In contrast, CBCT is suitable for modeling the nasal fossae and maxillary sinus for early-stage endoscopic training and patient-specific procedural planning [11,14].

In dentistry, the consistent use of CBCT has enabled the fabrication of highly accurate 3D-printed models for implant planning, maxillofacial surgery, orthodontic assessment, and educational training [1,11]. CBCT-based measurements of bone quality and mandibular morphology further enhance diagnostic workflows, particularly in patients with low bone mass, and translate effectively into printed replicas with reliable dimensional fidelity [15–17]. These models support both clinical decision-making and hands-on training in a wide variety of dental procedures.

Regarding materials, photopolymer resins, composite formulations, and polylactic acid (PLA) remain central to the production of anatomical models across disciplines. Resin-based prints are particularly useful in otologic and skull base simulations. At the same time, PLA offers broad applicability in dentistry and the development of experimental constructs, such as drug-eluting sinus stents [6, 10, 12, 18]. Multi-material printing technologies further expand the fidelity and versatility of these models, enabling simulation of heterogeneous tissue properties within a single construct.

Overall, the evidence highlights a complementary role of CT and CBCT in producing anatomically accurate and clinically relevant 3D-printed models. The interdisciplinary integration of imaging, additive manufacturing, and polymer science continues to enhance surgical training, improve patient communication, and open new translational avenues in both ENT and dental fields. CT remains superior for high-complexity ENT models, whereas CBCT provides an optimal balance of cost, dose, and resolution for dentoalveolar and maxillary sinus applications.

4. Discussion

The findings of this review underscore the growing importance of 3D-printed anatomical models derived from CT and CBCT imaging in both otorhinolaryngology and dental practice. Although initially adopted in otology as an alternative to cadaveric temporal bone dissection, the applications of 3D-printed models have expanded significantly, driven by improvements in imaging technologies, segmentation processes, and printing materials. Across disciplines, these models have demonstrated substantial educational and clinical value, offering realistic anatomical replicas that enhance procedural understanding, improve surgical confidence, and support patient communication.

In contrast, CBCT has emerged as the dominant imaging modality in dentistry due to its lower radiation dose, accessibility, and ability to capture high-resolution images of the maxillofacial complex. CBCT-derived models have demonstrated excellent accuracy in dental implant planning, orthodontic evaluation, and maxillofacial surgery, as well as in assessing bone quality in patients with low bone mass [1,11,15–17]. Their widespread use in education further underscores their value, as trainees can practice implant placement, osteotomy preparation, or sinus lift planning using anatomically faithful and easily reproducible models.

Although CBCT is limited in its ability to replicate the fine anatomical details of deeper sinonasal structures, its application in ENT is still noteworthy. CBCT-based models are well-suited for early-phase training in functional endoscopic sinus surgery (FESS), especially for procedures involving the nasal cavity and maxillary sinus. Studies have demonstrated that CBCT datasets reliably reproduce linear and volumetric sinus measurements, providing sufficient anatomical detail for basic endoscopic orientation and procedural rehearsal [11,14]. This makes CBCT particularly useful in interdisciplinary scenarios where dental pathology and rhinologic disease overlap, such as odontogenic sinusitis or maxillary sinus floor elevation.

Materials science represents another area where interdisciplinary integration has accelerated progress. Resin-based models remain the preferred option for high-precision ENT applications due to their rigidity and ability to replicate bone-like tactile feedback during drilling. Composite materials offer additional versatility, particularly when enhanced with fillers to improve mechanical realism for otologic or skull base procedures [6,10]. Meanwhile, PLA, widely used in dentistry, has demonstrated exceptional adaptability for educational models and continues to gain interest as a platform for biomedical innovation. The development of 3D-printed PLA sinus stents capable of delivering corticosteroids to support postoperative healing exemplifies the expanding translational potential of additive manufacturing [18].

A critical comparison of ENT and dental applications highlights distinct differences in imaging requirements and downstream printing fidelity. ENT surgical training demands precise reconstruction of thin bony lamellae, consistent grayscale calibration, and robust segmentation workflows—criteria that strongly favor CT.

A consistent theme across the studies reviewed is the gradual replacement of cadaveric specimens with 3D-printed anatomical models for surgical training. Restricted access to cadaver material, regulatory barriers, and increasing ethical concerns have positioned 3D printing as a viable, reproducible, and cost-effective alternative. Surgical trainees repeatedly report improved confidence and enhanced comprehension of anatomical relationships following training on 3D-printed models [5,7]. At the same time, patient-specific models have been successfully used to improve communication with patients by illustrating anatomic variations and procedural steps, ultimately enhancing treatment adherence and reducing medico-legal misunderstandings [13,14].

An additional challenge identified in this review is the lack of standardized validation frameworks across ENT and dental specialties. Many studies report accuracy metrics inconsistently or without reference standards, hindering quantitative comparison. Furthermore, cost analyses and radiation-dose comparisons are seldom integrated into methodological descriptions, despite their practical relevance when choosing between CT and CBCT for both clinical and educational purposes. Addressing these gaps in future research will enable more robust cross-disciplinary comparisons and support evidence-based selection of imaging modalities for 3D printing workflows [22].

Beyond the technical considerations related to anatomical fidelity, segmentation accuracy, and material selection, the development of CT- and CBCT-based 3D-printed replicas also requires adherence to robust standards of data protection and ethical governance. The workflow inherently involves the acquisition, transfer, and processing of sensitive imaging data, which must comply with national and European regulatory frameworks to ensure confidentiality and secure handling. Recent analyses of data management practices in Romanian public healthcare have revealed that digitalization presents significant challenges in maintaining a GDPR-compliant infrastructure, underscoring the need for transparent consent procedures, clear data pathways, and controlled access at every step of the imaging-to-print pipeline. Integrating these regulatory considerations strengthens the translational value of 3D-printed anatomical models and aligns the field with current expectations for ethical and legally responsible clinical innovation [19].

Overall, the integration of CT and CBCT imaging with modern 3D printing technologies has created a robust platform for surgical simulation, clinical planning, and interdisciplinary collaboration. The convergence of ENT, dentistry, and materials science is driving new applications that extend beyond education into personalized medicine and the development of therapeutic devices. As imaging and printing technologies continue to evolve, 3D-printed anatomical models are likely to become increasingly sophisticated, clinically impactful, and central to modern surgical training paradigms. This review provides a consolidated interdisciplinary perspective that clarifies when CT is essential, when CBCT is sufficient, and how current material and workflow limitations should influence 3D-model selection for specific clinical and educational purposes [20].

5. Limitations

This systematic review has several limitations that should be taken into account when interpreting the findings. The included studies were heterogeneous in design, methodology, and outcome reporting, which limited the possibility of conducting a meta-analysis and necessitated a narrative synthesis. Variability in imaging protocols, segmentation workflows, printer technologies, and material selection contributed to differences in anatomical accuracy across studies, making direct comparison challenging. Many investigations focused on specific anatomical regions, such as the temporal bone or maxillary sinus, which may limit the generalizability of their findings to other areas of the sinonasal or craniofacial complex. Additionally, the quality of reporting was inconsistent, with some studies providing detailed validation metrics while others lacked quantitative accuracy assessment or comprehensive methodology descriptions.

Another limitation is the uneven distribution of evidence across specialties. The literature on CT-based models, particularly for otologic and skull base applications, is more mature than the evidence supporting CBCT-derived models in ENT practice. Conversely, the dental literature relies heavily on CBCT, yet its applicability to more complex rhinologic procedures remains limited by inherent imaging constraints. The absence of standardized validation criteria or universally accepted accuracy thresholds further complicates cross-study comparisons. Finally, most studies were conducted in controlled laboratory or educational settings, and relatively few evaluated the real-world clinical impact of 3D-printed models on surgical outcomes, patient safety, or cost-effectiveness.

A further methodological limitation is the inconsistent reporting of radiation-dose metrics and cost comparisons between CT and CBCT across the included studies, despite these being critical parameters for selecting an imaging modality for 3D model generation. The incomplete documentation of imaging parameters (voxel size, field of view, and grayscale calibration) in several studies also limited the ability to correlate dataset characteristics with printing fidelity. Moreover, the frequent absence of standardized segmentation workflows and reproducibility testing limits the robustness of inter-study comparisons, highlighting the need for unified methodological guidelines for future research[21].

Finally, although this review synthesizes interdisciplinary evidence from ENT, dental, and biomaterials literature, the heterogeneity of study objectives, anatomical targets, and printing technologies may still lead to a degree of interpretive bias. This reflects a broader limitation of the field itself, where standardization remains insufficient and reporting practices vary substantially between specialties.

6. Conclusions

Three-dimensional printing has become an increasingly valuable tool across otorhinolaryngology, dental practice, and biomaterials science, enabling the creation of patient-specific anatomical models that support surgical training, clinical decision-making, and innovation in the development of therapeutic devices. CT-derived models remain the gold standard for replicating the intricate anatomy of the temporal bone, ethmoid labyrinth, and sphenoid sinus, offering the level of detail required for advanced endoscopic and otologic procedures. CBCT-based models demonstrate excellent performance in the dentoalveolar region and maxillary sinus, where they provide reliable anatomical accuracy for training, treatment planning, and diagnostic evaluation.

The interdisciplinary integration of imaging technologies, segmentation workflows, and polymer-based materials continues to expand the applications of 3D-printed models, improving their fidelity and functional relevance. Resin, composite, and PLA-based constructs each contribute unique advantages, supporting both high-precision simulation and novel translational applications such as drug-delivering stents. As access to cadaveric specimens becomes increasingly restricted, 3D printing offers a reproducible, ethically sound, and cost-effective alternative for hands-on surgical education.

Based on the comparative synthesis of ENT and dental applications, CT should be preferentially selected for highly complex anatomical regions requiring superior contrast resolution and fine bony detail. In contrast, CBCT offers an advantageous balance of radiation dose, cost, and spatial resolution for dentoalveolar and maxillary sinus applications. This complementary use of the two imaging modalities represents a key interdisciplinary insight supported by the reviewed evidence.

In conclusion, this review presents a comprehensive framework that clarifies when CT is essential, when CBCT is sufficient, and how material-related factors influence the fidelity and usability of 3D-printed anatomical replicas, thereby guiding clinicians and educators in selecting the most suitable imaging-to-print workflow for their specific objectives.

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