ИНТЕГРАЦИЯ ЦИФРОВОГО ПЛАНИРОВАНИЯ В ЧЕЛЮСТНО-ЛИЦЕВУЮ ХИРУРГИЮ

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Аннотация: *в современной челюстно-лицевой хирургии цифровое планирование перешло от вспомогательного этапа визуализации к клинически значимому этапу. Оно связывает 3D визуализацию, хирургическое планирование, автоматизированное проектирование и производство, а также интраоперационную передачу с помощью шин, направляющих для разрезов, имплантатов, изготовленных по индивидуальным параметрам пациента, навигации или смешанной реальности. Несмотря на широкое внедрение, многие рабочие процессы остаются лишь частично интегрированными. В статье обобщаются последние клинические и технические данные по ортогнатической хирургии, травматологии, реконструкции и имплантологическим процедурам, с акцентом на измеримые точки отказа и практические средства контроля, обеспечивающие возможность аудита всего процесса. Данные свидетельствуют о том, что клиническая польза наиболее устойчива, когда интеграция рассматривается как инженерная и управленческая проблема: регистрация количественно оценивается, сегментация обеспечивается с помощью взвешенной проверки, устройства для передачи проверяются непосредственно в месте оказания медицинской помощи, а послеоперационный аудит используется в качестве обратной связи для непрерывного совершенствования. На основе полученных результатов в обсуждении представлена интеграционная модель, которая сочетает в себе планирование погрешностей и верификацию с обратной связью.*
Ключевые слова: *виртуальное планирование хирургических операций, CAD/CAM, хирургические шаблоны, хирургическая навигация, КЛКТ, КТ, сегментация с использованием глубокого обучения, челюстно-лицевая реконструкция, ортогнатическая хирургия.*

INTEGRATION OF DIGITAL PLANNING IN MAXILLOFACIAL SURGERY

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Abstract: *Digital planning has moved from an adjunct visualization step to a clinically consequential execution layer in contemporary maxillofacial surgery. It links volumetric imaging, virtual surgical planning, computer-aided design and manufacturing, and intraoperative transfer via splints, cutting guides, patient-specific implants, navigation, or mixed reality. Despite broad adoption, many workflows remain only partially integrated. This article synthesizes recent clinical and technical evidence across orthognathic surgery, trauma, reconstruction, and implant-related procedures, with emphasis on measurable points of failure and on practical controls that make the pipeline auditable. Evidence indicates that clinical benefit is most consistent when integration is treated as an engineering and governance problem: registration is quantified, segmentation is quality-assured with risk-weighted verification, transfer devices are checked at the point of care, and postoperative audit is used as feedback for continuous improvement. On the basis of these findings, the discussion articulates an integration model for routine practice that combines error budgeting and closed-loop verification.*
Keywords: *virtual surgical planning, CAD/CAM, surgical guides, surgical navigation, CBCT, CT, deep learning segmentation, maxillofacial reconstruction, orthognathic surgery.*

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INTRODUCTION

Maxillofacial surgery occupies a narrow operating margin between functional restoration, aesthetic balance, and complication avoidance. The same osteotomy or fixation strategy can influence occlusion, airway patency, facial symmetry, temporomandibular joint loading, and long-term relapse. At the same time, millimetric deviations near the mandibular canal, mental foramen, orbital apex, or skull base can translate into neuropathic pain, diplopia, hemorrhage, or irreversible vision compromise. These constraints make planning and execution inseparable. In complex cases, planning is not merely preoperative thinking; it is the mechanism through which risk is allocated and controlled across the entire procedure.

Over the last two decades, planning has shifted from two-dimensional cephalometrics, model surgery on stone casts, and manual splint fabrication toward workflows that begin with volumetric imaging and end with digitally specified transfer artifacts. Virtual surgical planning (VSP) and CAD/CAM can improve predictability and standardize decisions that previously depended heavily on individual experience, yet accuracy outcomes remain variable across institutions and procedures [1, p. 34]. The variability is rarely explained by one algorithmic step. More often it arises from boundary conditions between modules, such as misregistration between CBCT and intraoral scans, unrecognized segmentation errors in low-contrast regions, or imperfect seating of a guide that converts a precise plan into an imprecise execution.

A central clinical challenge is that digital pipelines can fail silently. A three-dimensional model may appear plausible while the coordinate frame is offset, the occlusal relationship is inconsistent with the operative position, or the mandibular canal segmentation is locally wrong in the region that matters most. Systematic reviews in orthognathic surgery report mean deviations within clinically acceptable thresholds, but they also document that accuracy differs by axis, by landmark, and by step in the workflow, reflecting a multi-source error budget rather than a single controllable parameter [13].

Deep learning has compressed the time required to segment maxillofacial anatomy from CT and CBCT, and robust open-source tools now deliver automated segmentation of key structures used in surgical planning [3]. However, automation introduces new failure modes: clinicians may over-trust an output whose uncertainty is not visible, and safety-critical errors may cluster near foramina or artifact-prone areas [7, p. 5842]. Intraoperative navigation and mixed reality systems seek to make plan transfer observable, but their performance is bounded by registration quality, reference stability, and drift, rather than by display fidelity alone [12].

This review addresses integration as a clinically grounded systems problem. The objective is to connect technical modules to pragmatic endpoints such as transfer accuracy, operative time, intraoperative revisions, and complication risk, and to articulate a set of integration controls that can be deployed in routine practice. The analysis treats the workflow as an auditable chain, identifying where error is introduced, how it propagates, and which measurements and verification steps most effectively contain it.

MATERIALS AND METHODS

A narrative review design was selected because evidence on digital planning spans heterogeneous procedures and technology stacks, with outcome definitions that vary across orthognathic surgery, trauma, reconstruction, and implant-related interventions. Targeted searches prioritized 2020 to 2025 publications in oral and maxillofacial surgery, craniofacial surgery, dentomaxillofacial radiology, and computer-assisted surgery. Search concepts included virtual surgical planning, CAD/CAM splints and cutting guides, patient-specific implants, 3D printing workflows, surgical navigation, augmented or mixed reality, and deep learning segmentation in CT and CBCT.

Eligible sources included systematic reviews, structured reviews, narrative reviews with technical scope, clinical case series with quantitative accuracy reporting, cadaver validation studies of navigation or mixed reality, and benchmarking studies of automated segmentation on clinically diverse datasets.

To support a practice-facing integration model, the synthesis prioritized measurability and auditability. Where available, studies reporting planned-to-achieved deviations, registration error metrics, or device fit outcomes were weighted more heavily than purely descriptive reports.

RESULTS

Table 1. Integration components of digital planning and their primary clinical endpoints.

Workflow component	Typical technologies	Primary measurable endpoint	Common failure mode in practice
Data acquisition and multimodal registration	CBCT or CT; MRI when indicated; intraoral scanning; photogrammetry; surface-to-volume registration	Target registration error; anatomical fidelity; time to create a composite model usable for planning	Misregistration from artifacts, limited field of view, inconsistent bite position, unstable fiducials, or unrecognized coordinate-frame drift
Segmentation and model construction	Manual or semi-automatic contouring; deep learning segmentation with structured quality assurance	Structure-specific accuracy for bone, teeth, canals and sinuses; inter-operator variability; time to model	Locally incorrect boundaries in low-contrast or artifact regions; over-trust in automated contours; inconsistent smoothing that alters surgical interfaces

Virtual planning and constraint definition	Osteotomy planning; occlusal setup; plate and implant design; implant trajectory planning; risk corridor definition	Planned-to-achieved skeletal movement; clearance from critical anatomy; reproducibility across operators	Unquantified uncertainty; planning assumes a stable intraoperative reference that later shifts; constraints are implicit rather than explicitly measured
Transfer to the operating room	3D-printed guides and splints; patient-specific plates or implants; optical or electromagnetic navigation; mixed reality visualization	Transfer accuracy; operative time; need for intraoperative revisions; intraoperative deviation checks	Guide instability or seating error; reference marker loosening; tracking occlusion; latency; insufficient verification at the moment of transfer
Postoperative verification and feedback	Postoperative CT or CBCT alignment to plan; deviation maps; navigation logs; quality reports	Deviation distributions; root cause attribution; longitudinal performance monitoring	Absence of routine audit; missing governance for versioning of software and printers; lack of feedback loop that turns deviations into process improvement

Orthognathic surgery illustrates how upstream acquisition and downstream transfer can dominate the error budget. Systematic evidence indicates that deviations below approximately 2 mm or 2 degrees are commonly considered acceptable in clinical reporting, yet errors cluster along specific axes and landmarks, especially where vertical control, condylar seating, or sagittal repositioning are sensitive to intraoperative technique and occlusal instability [13]. These patterns reinforce that a plan must be paired with measurable transfer checks, because precision in the virtual environment does not guarantee precision in the operative environment.

Reconstruction and trauma present complementary integration constraints. In oncologic reconstruction, VSP and CAD/CAM guides support reproducible osteotomies and predictable alignment of donor and recipient segments, while patient-specific plates and implants can streamline fixation when fit is reliable [9, p. 351]. In trauma, swelling, comminution, and time pressure increase reliance on registration and on intraoperative verification. Mixed reality planning for patient-specific orbital plates has been evaluated against conventional planning workflows, reflecting a trend toward bringing the planned contour closer to the operative field, although performance remains bounded by registration and user interaction [4].

Automation is increasingly central to planning economics and to workflow scalability. DentalSegmentator, a robust open-source deep learning tool, reports fully automatic segmentation of key dentomaxillofacial structures on CT and CBCT, including the mandibular canal, using a large and diverse dataset [3]. However, detailed studies of canal segmentation emphasize that local performance can degrade near foramina and artifact-prone areas, supporting a safety model in which automated segmentation is paired with structured human verification focused on risk zones [7].

Navigation, augmented reality, and mixed reality are increasingly used to make plan transfer observable. A cadaver evaluation of augmented reality navigation for zygomatic implant placement demonstrates feasibility, while highlighting dependence on stable registration and tracking [6]. A prospective clinical trial of a portable mixed reality navigation system suggests that head-mounted approaches can reduce infrastructure burden, but also underscores the need for robust fixation and registration strategies suitable for routine operating conditions [14, p. 10]. A broader navigation review synthesizes that clinical impact is determined by procedure-specific integration choices, including reference strategy, verification routines, and error monitoring, rather than by navigation modality alone [15, p. 283].

An explicit error budget provides a clinically interpretable bridge between engineering metrics and operative decision-making. From a coordinate-transform perspective, the planned target is mapped through a sequence of transformations: image acquisition, multimodal registration, segmentation-driven model definition, virtual plan creation, device manufacturing or navigation setup, and intraoperative transfer. Each transformation contributes uncertainty that is partly systematic and partly random. When uncertainty is not explicitly tracked, teams tend to focus on the visually impressive steps, such as three-dimensional simulation or mixed reality display, while overlooking more prosaic contributors such as bite registration, scanner artifacts, and guide seating. A practical integration approach is to define procedure-specific tolerance bands and to assign measurement checkpoints to the transformations that dominate risk. For example, implant trajectory planning near the mandibular canal benefits from a conservative clearance margin whose size reflects worst-case local segmentation uncertainty, not only the nominal drilling accuracy.

Clinical implementability depends on turning these measurements into workflow gates that do not overload the operating team. In mature pipelines, verification becomes selective and risk-weighted. Registration is checked against a small set of anatomical landmarks that are both visible and functionally relevant, segmentation review concentrates on risk corridors rather than on the entire model, and guide seating is validated by tactile stability and interface fit before irreversible steps such as osteotomy completion or drilling. Navigation or mixed reality then functions as a secondary verification channel. This layered design creates redundancy and reduces reliance on any single module, aligning with the broader trend toward hybrid navigation systems that combine static and dynamic elements depending on procedure needs [11, p. 280].

Imaging strategy and acquisition parameters were repeatedly identified as upstream determinants of downstream accuracy. CT and CBCT each impose distinct constraints. CT offers more reliable soft-tissue visualization and is less sensitive to certain metallic distortions, while CBCT is widely used because of accessibility and lower dose in many dentomaxillofacial scenarios, albeit with a higher risk of scatter artifacts that distort the dental arches and thin bony cortices. Clinical VSP protocols therefore commonly combine CBCT with intraoral scans or scanned casts to restore high-fidelity dentition, and some protocols employ multi-scan or triple-scan approaches to improve registration between modalities [1, p. 34]. From an integration standpoint, the practical endpoint is not image quality in isolation but the accuracy and reproducibility of the composite model used for planning, since all device fit and navigation registration depend on it.

A second recurring pattern is that successful integration depends on explicitly defining the reference anatomy that remains stable across time points. In orthognathic surgery, the occlusal relationship can change between imaging, splint fabrication, and operative positioning, and the mandible can seat differently under anesthesia. These factors can shift the effective coordinate frame even when the skull base appears well aligned. Studies describing acceptable mean deviations still report axis-specific outliers, which suggests that the integration control should include reference validation at known interfaces such as occlusal seating and condylar positioning, rather than assuming that global superimposition implies local fidelity [14, p. 281].

Manufacturing and device realization introduce an additional, often underestimated, component of the error budget. Guide-based transfer and patient-specific plates rely on printer calibration, material shrinkage, post-processing, and sterilization effects, all of which can influence fit and stability. Recent reviews of 3D-printed surgical devices emphasize that outcomes depend not only on geometric design but also on workflow controls such as printer validation, material selection, build orientation, and quality documentation, particularly for devices intended to interface with bone or to guide drilling trajectories [4]. In practice, the clinically relevant endpoint is seating stability and repeatability under operative forces, since a guide that rocks or binds can convert a precise plan into a systematic offset at the osteotomy or drilling corridor.

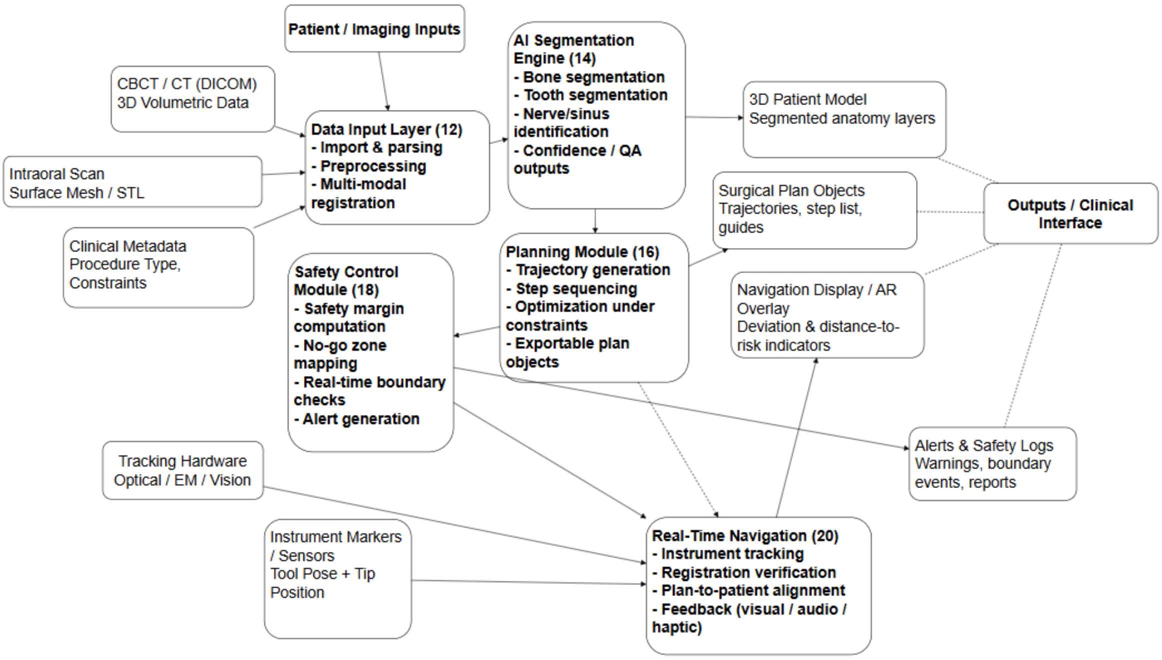

Fig. 1. Block diagram illustrating the overall architecture of the AI-assisted surgical planning and navigation system

DISCUSSION

Digital planning delivers clinical value when it functions as a risk-control layer and when residual uncertainty remains visible at the point of decision. This requirement changes how the workflow is designed. It is insufficient for each module to perform well in isolation; the chain must be engineered so that errors introduced upstream are measured, bounded, and either corrected or compensated downstream. In practice, the most consequential integration failures are boundary failures. They arise when a transformation between coordinate frames is accepted without verification, when a segmented boundary is assumed to be ground truth without risk-weighted review, or when a transfer device is assumed to seat correctly without a point-of-care check.

Registration is a primary determinant of safety and accuracy because it defines the coordinate frame in which all subsequent decisions are made. In orthognathic workflows, occlusal discrepancies between imaging and surgery, condylar seating variation, and field-of-view limitations can produce offset models whose appearance remains plausible. In reconstruction and trauma, stable landmarks may be absent or altered, forcing reliance on fiducials, contralateral mirroring, or hybrid surface and feature matching. The integration implication is straightforward: registration must be treated as a measurable clinical action, not as an invisible preprocessing operation. The workflow benefits from redundancy, such as combining volumetric registration with surface checks at known anatomical interfaces, and from explicit re-registration checkpoints when the reference array is moved or when soft tissue deformation is expected [7].

Segmentation defines the geometry of risk corridors and therefore functions as a safety layer rather than a purely technical convenience. Deep learning can reduce time and inter-operator variability, and multiclass models enable full reconstruction of structures required for VSP and implant risk assessment [10]. Yet the clinical significance of segmentation performance is not captured by global overlap metrics alone. Errors that matter concentrate in thin structures and in regions degraded by scatter and low contrast. Mandibular canal localization illustrates this point: performance is strong across much of the canal length but weaker near foramina and in challenging regions, which are exactly the areas where surgical corridors are narrow [15]. A clinically robust integration pattern is therefore to pair automated segmentation with uncertainty cues and a structured verification gate focused on risk zones, such as the canal trajectory, the planned osteotomy margin, and the planned drilling corridor [13].

Plan transfer can be framed as static transfer and dynamic verification. Static transfer encodes the plan into splints, cutting guides, and patient-specific plates. This approach is efficient when seating is reliable and when manufacturing tolerances are controlled, and it is therefore widely used in orthognathic surgery and free-flap reconstruction [8, p. 345]. Dynamic verification adds navigation or mixed reality to make plan execution observable in real time. Its clinical value is less about replacing guides and more about detecting and correcting seating errors, reference drift, and deviations before they become irreversible. Evidence from mixed reality and augmented reality studies indicates feasibility, but also emphasizes that the dominant error source is registration quality, including fixation of the reference and resistance to drift under operative manipulation [3, p. 4482]. This is consistent with broader reviews that position navigation as a systems intervention whose benefit depends on how verification routines are embedded in the operative choreography [13, p. 7].

Closed-loop audit is the least consistently implemented step in routine practice, yet it is the step that converts digital planning from a one-off preoperative activity into a continuously improving clinical system. Postoperative alignment of imaging to the preoperative plan produces deviation maps that can localize systematic errors. A cluster of deviations at guide interfaces points toward seating or manufacturing issues, while a consistent axis-specific bias can indicate an occlusion capture problem or a condylar seating effect. Without audit, institutions can introduce new printers, new software versions, or new segmentation models without detecting gradual drift in performance. This governance problem is increasingly relevant as AI-assisted components become more common in planning pipelines [9].

Model governance and cybersecurity are increasingly intertwined with clinical safety as planning becomes cloud-connected and as AI components are updated. Segmentation models can drift in performance when deployed on scanners, protocols, or patient populations that differ from the training distribution, and post-processing defaults can change the geometry of a guide interface without the change being visible to the surgeon. From a governance standpoint, institutions benefit from version control for planning software, printer firmware, and AI models, along with minimal acceptance testing that includes representative scans with artifacts and challenging anatomy. Ethically, audit trails should enable attribution of decisions, distinguishing automated outputs from clinician-confirmed structures and recording the sequence of edits, which is consistent with broader discussions of responsible AI adoption in oral and maxillofacial practice [10, p. 282].

These integration principles motivated the development of a planning and navigation system that operationalizes measurement and safety gating across the pipeline. In this system, multimodal inputs such as CBCT or CT and intraoral surface data are registered into a common coordinate space, followed by automated segmentation of bone, dentition, and critical structures. Planning defines not only target movements or trajectories but also explicit constraints expressed as quantifiable clearances to risk structures, which are monitored as part of a safety control layer. Intraoperative navigation then compares instrument position and execution against the planned constraints in real time, allowing verification of transfer rather than reliance on assumption. Finally, postoperative comparison of achieved and planned geometry is treated as a routine quality report. The role of this example is to show that integration can be encoded into concrete mechanisms. It illustrates how a workflow can be designed so that the critical question is not whether software can generate a plan, but whether the plan can be executed with measurable confidence.

A final integration constraint is human factors. Even technically robust systems can underperform when roles and responsibilities are unclear. Digital planning introduces new tasks such as scan protocol selection, segmentation validation, guide inspection, and navigation calibration. In practice, reliability improves when these tasks are assigned to defined roles and documented as part of the surgical checklist, similar to how implant component verification or antibiotic prophylaxis are standardized. Training is most effective when it is tied to measurable outputs, such as landmark-based registration checks and postoperative deviation reports, because these metrics convert planning expertise into reproducible team performance rather than personal tacit knowledge.

CONCLUSIONS

Digital planning is foundational in modern maxillofacial surgery, but dependable clinical value depends on integration and verification. Across orthognathic, reconstructive, and implant-related procedures, reliable benefit is most consistently observed when registration and plan transfer are treated as measurable, auditable steps. Deep learning segmentation improves scalability when uncertainty is explicit and when human validation is structured as a safety gate. Navigation and mixed reality approaches contribute when they are deployed to verify transfer and detect drift, with registration quality and reference stability as dominant determinants. Routine postoperative deviation reporting remains underused and represents a practical opportunity to improve safety, reproducibility, and governance as digital pipelines evolve.

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