



www.bioinformation.net
Volume 22(9)



Research Article

Received September 1, 2026; Revised September 30, 2026; Accepted September 30, 2026, Published September 30, 2026

DOI: 10.6026/973206300225920

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478

2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Edited by Ruby Singh

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Citation: Vashisht *et al.* Bioinformation 22(9): 5920-5923 (2026)

Artificial intelligence-assisted versus traditional freehand planning for zygomatic implant placement: An *in vitro* comparative study

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Abstract:

Planning zygomatic implants in severely atrophic maxillae remains technically challenging and carries a risk of anatomical complications. Therefore, it is of interest to compare the AI-assisted and traditional planning in 50 hemi-maxilla models. AI-assisted planning significantly reduced entry-point, apex and angular deviations while shortening planning time ($p < 0.001$). It also achieved greater cortical bone contact and fewer simulated maxillary sinus perforations than traditional planning. Thus, data shows that AI-assisted planning as a more accurate and efficient approach for zygomatic implants rehabilitation.

Keywords: Zygomatic implants, artificial intelligence (AI), digital implant planning, computer-assisted surgery, accuracy, cortical bone contact, sinus perforation, atrophic maxilla

Background:

Zygomatic implants provide a graft less solution for rehabilitation of the severely atrophic or resected edentulous maxilla by anchoring long implants in the zygomatic bone rather than the deficient alveolar ridge [1]. Systematic reviews consistently report implant survival rates exceeding 95%, demonstrating their long-term clinical predictability. However, surgical and prosthetic complications such as maxillary sinusitis, soft-tissue dehiscence and occasional orbital or infratemporal injury remain concerns, largely because of inaccuracies in implant trajectory rather than failure of osseointegration [2]. Owing to the long and anatomically complex pathway traversing the maxillary sinus and lying close to the orbit and infratemporal fossa, even minor deviations at the implant entry point may result in substantial apical displacement, emphasizing the importance of precise preoperative planning [3]. Digital technologies have transformed zygomatic implant planning by improving accuracy and reducing operator-dependent variability. Computer-assisted approaches, including static surgical guides and dynamic navigation have showed significantly lower entry-point, apex and angular deviations than conventional freehand techniques [4]. Navigation-assisted surgery also enhances surgical predictability and minimizes complications, although technical expertise, increased cost and a recognized learning curve remain important limitations [5]. Consequently, there is growing interest in more automated planning methods that reduce dependence on operator experience while maintaining high surgical accuracy. Artificial intelligence (AI) has recently emerged as a promising tool in implant dentistry by automating image segmentation, anatomical landmark identification and implant trajectory planning. AI-based systems can rapidly analyze cone-beam computed tomography (CBCT) datasets, identify critical anatomical structures and recommend optimal implant positions while minimizing potential surgical risks [6]. Systematic reviews have shown that AI-assisted implant planning improves planning efficiency and reproducibility compared with conventional manual workflows, although evidence from clinical validation studies remains limited [7]. Deep learning algorithms have also demonstrated high accuracy in bone quality assessment, implant site selection and guided surgical

planning, supporting their expanding role throughout the digital implant workflow [8]. Despite these advances, evidence specifically evaluating AI-assisted planning for zygomatic implants remains scarce. Zygomatic implant placement presents greater technical challenges than conventional implant surgery because of extended implant length, variable bone density and close proximity to vital anatomical structures. Therefore, this procedure represents an ideal application for AI-assisted planning, where improvements in accuracy may translate directly into enhanced surgical safety and treatment predictability [9]. The present *in vitro* study directly compared AI-assisted and traditional clinician-led planning of zygomatic implants using 50 hemi-maxilla models. Planning accuracy was assessed by entry-point, apex and angular deviation, while efficiency and safety were evaluated through planning time, cortical bone contact and simulated maxillary sinus perforation [10]. Therefore, it is of interest to evaluate the comparative accuracy, efficiency and safety of AI-assisted and traditional manual planning for zygomatic implants using an *in vitro* model.

Materials and Methods:

Fifty *in vitro* hemi-maxilla/zygomatic bone models (21 left-sided, 29 right-sided) were used; each assigned a unique specimen identifier. Pre-planning cone-beam computed tomography (CBCT) was used to record zygomatic bone density in Hounsfield units (HU) at the intended implant site (mean 854.0 ± 69.9 HU; range 698.5-1042.7 HU). A single planned implant length was assigned per specimen (range 35-50 mm) and held identical for both planning methods, so that any difference in outcome could be attributed to the planning method rather than to implant geometry. Ethical was obtained from Institutional Ethics Committee of Seema Dental College and Hospital (Reference No.: SDCH/MDS-PROSTHO/IEC/09/2024) dated 14 February 2024. For each specimen, two independent trajectories were planned to the same ideal target: (i) a traditional protocol, in which the implant path was determined manually on CBCT sections by a trained operator applying conventional anatomical landmarks and visual judgement and (ii) an AI-assisted protocol, in which planning software incorporating automated bone, sinus and trajectory-optimisation algorithms proposed the implant path,

which the operator could review before finalisation. For both methods, the following outcomes were recorded by superimposing the planned trajectory on the achieved (simulated) trajectory: linear deviation at the coronal entry point (mm), linear deviation at the implant apex (mm), angular deviation of the implant axis (degrees), time taken to complete planning (minutes), percentage of the implant surface in cortical bone contact and presence or absence of simulated maxillary sinus wall perforation (binary). Continuous outcomes (entry-point deviation, apex deviation, angular deviation, planning time, cortical bone contact) were summarised as mean $\pm$ standard deviation and compared between methods within each specimen using paired-samples t-tests. Sinus perforation, a binary outcome, was compared using McNemar's test for paired proportions. A two-sided p-value <0.05 was considered statistically significant. Analyses were performed on all 50 paired specimens with no missing data.

Results:

All 50 specimens contributed complete paired data for both planning methods. **Table 1** summarises specimen characteristics and **Table 2** presents the comparative accuracy, efficiency and safety outcomes. AI-assisted planning produced significantly smaller entry-point deviation than traditional planning (1.00 ± 0.33 mm vs 1.77 ± 0.43 mm; $t=9.15$, $p<0.001$), smaller apex

deviation (1.43 ± 0.39 mm vs 2.31 ± 0.68 mm; $t=7.91$, $p<0.001$) and smaller angular deviation ($2.40 \pm 0.97^\circ$ vs $4.69 \pm 1.17^\circ$; $t=10.53$, $p<0.001$). The magnitude of these differences - a roughly 45–55% relative reduction in linear and angular deviation was consistent across all three accuracy parameters. Planning time was reduced by more than half with AI assistance (7.02 ± 1.80 minutes vs 18.59 ± 4.83 minutes; $t=16.63$, $p<0.001$), representing the largest relative effect of any parameter measured. Percentage cortical bone contact was higher for AI-assisted trajectories ($85.58 \pm 5.12\%$ vs $78.65 \pm 6.36\%$; $t=-5.96$, $p<0.001$). Simulated maxillary sinus wall perforation occurred in 2 of 50 specimens (4.0%) planned with AI assistance compared with 9 of 50 specimens (18.0%) planned traditionally; this difference was statistically significant on McNemar's test for paired proportions ($p=0.039$), with 8 specimens perforated only under traditional planning against 1 perforated only under AI-assisted planning. Baseline bone density was not significantly correlated with the magnitude of angular deviation for either traditional planning ($r=0.24$, $p=0.099$) or AI-assisted planning ($r=0.19$, $p=0.189$), nor with the size of the improvement in angular deviation attributable to AI assistance ($r=0.06$, $p=0.672$), suggesting that the accuracy benefit of AI-assisted planning was not confined to specimens with more favourable bone density.

Table1: summarises specimen characteristics

Specimen characteristic	Value	Notes
Hemi-maxilla specimens (n)	50	Left n=21; Right n=29
Bone density (Hounsfield units)	854.0 ± 69.9	Range 698.5–1042.7 HU
Planned implant length (mm)	$42.95 \pm$ mixed	Range 35–50 mm, identical per specimen for both methods

Table 2: Summary of comparative outcomes, AI-assisted versus traditional zygomatic implant planning (n=50 paired specimens)

Parameter	Traditional (Mean $\pm$ SD)	AI-Assisted (Mean $\pm$ SD)	Mean Difference	Paired t-test (t, p-value)	Favours
Entry-point deviation (mm)	1.77 ± 0.43	1.00 ± 0.33	0.77	$t=9.15$, $p<0.001$	AI
Apex deviation (mm)	2.31 ± 0.68	1.43 ± 0.39	0.88	$t=7.91$, $p<0.001$	AI
Angular deviation ($^\circ$)	4.69 ± 1.17	2.40 ± 0.97	2.29	$t=10.53$, $p<0.001$	AI
Planning time (min)	18.59 ± 4.83	7.02 ± 1.80	11.57	$t=16.63$, $p<0.001$	AI
Cortical bone contact (%)	78.65 ± 6.36	85.58 ± 5.12	-6.93	$t=-5.96$, $p<0.001$	AI
Sinus perforation, n (%)	9 (18.0%)	2 (4.0%)	7 fewer	McNemar $p=0.039$	AI

Discussion:

In this *in vitro* comparison of 50 paired hemi-maxilla specimens, AI-assisted planning outperformed traditional manual planning across every measured dimension: entry-point, apex and angular deviation were all smaller; planning time was shorter; cortical bone contact was greater; and simulated sinus perforation was less frequent. The pattern and approximate magnitude of the accuracy gains are consistent with those reported for computer-assisted navigation relative to free-hand zygomatic implant placement, where pooled meta-analytic data likewise show smaller entry, apex and angular deviation for guided or navigated techniques than for a free-hand approach [11]. Dedicated *in vitro* comparisons of dynamic navigation against free-hand zygomatic implant placement have reported broadly similar directions of effect, although the size of the advantage has varied with navigation system, operator experience and anatomical complexity. The present findings extend this literature by showing that an AI-assisted planning workflow,

rather than intraoperative navigation per se, can deliver comparable or larger relative improvements in trajectory accuracy under controlled *in vitro* conditions. The reduction in planning time associated with AI assistance was the largest relative effect observed in this study and is consistent with reviews describing AI-based automation of bone, sinus and neurovascular segmentation as a route to greater planning efficiency without an apparent accuracy trade-off [12]. Because zygomatic implant planning is time-intensive and requires substantial operator expertise, a shorter, more standardised planning process could plausibly improve access to this technique in centres with less specialised experience, provided that clinical validation supports the *in vitro* accuracy findings reported here. The higher percentage cortical bone contact and lower simulated sinus perforation rate observed with AI-assisted planning are clinically relevant, since cortical bone engagement is closely linked to primary implant stability and Hounsfield-unit-based bone density assessment has previously been shown

to correlate with clinical stability measures in conventional implant sites [13]. Maxillary sinusitis remains the most frequently reported complication of zygomatic implant therapy in the wider clinical literature, so a reduction in simulated sinus wall perforation - even in an *in vitro* model - offers a plausible mechanistic explanation for why more accurate digital planning might translate into fewer sinus-related complications in clinical practice, although this link requires confirmation in prospective clinical cohorts. Bone density was not significantly associated with the magnitude of accuracy improvement attributable to AI assistance in this dataset, suggesting that the benefit of AI-assisted planning was not restricted to specimens with more favourable (denser) bone. This is a reassuring finding given that zygomatic implants are specifically indicated in patients with compromised or highly variable maxillary bone quality and it aligns with broader AI-in-implantology reviews describing automated planning tools as designed to generalise across a range of anatomical presentations rather than being optimised only for straightforward cases [14, 15]. Several limitations should be considered. First, this was an *in vitro* study using stereolithographic or polyurethane hemi-maxilla models rather than human cadavers or live patients; while such models allow tightly controlled paired comparisons, they cannot fully reproduce clinical variables such as soft-tissue handling, intraoperative bleeding, patient movement or long-term bone remodelling. Second, a single AI-assisted planning platform and a single traditional protocol were compared; results may not generalise to all commercially available AI planning tools, which differ in algorithmic approach and training data, as highlighted in recent scoping reviews of AI in pre-surgical implant planning [16, 17 and 18]. Third, planning accuracy was assessed on simulated superimposition rather than on an intraoperatively executed and independently verified trajectory, so translation of these findings into actual surgical accuracy will depend on the fidelity of subsequent implant placement, which was outside the scope of this study. Finally, although 50 paired specimens provided adequate power to detect the observed differences, the sample was not stratified by operator experience and learning-curve effects documented for other computer-assisted zygomatic implant techniques may also apply to AI-assisted planning and merit further study.

Conclusion:

AI-assisted planning showed high accuracy, short planning time

and few simulated sinus perforations than manual planning for zygomatic implants. AI-assisted planning also achieved greater cortical bone contact in this *in vitro* study. Further Clinical studies are needed to confirm whether these benefits help improve patient outcomes.

Conflict of interest: The authors declare no conflict of interest.

Funding: No external Funding was received.

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