MEDVIX PUBLICATIONS

Journal of Dentistry and Oral Health
Review Article | Open Access | ISSN 3071-5490 | Volume 03 | Issue 01

Artificial Intelligence and Robotic Surgery in Transcrestal Sinus Floor Elevation with Simultaneous Implant Placement: A Near-Future Paradigm

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Received date: 29 April 2026; **Accepted date:** 16 May 2026; **Published date:** 21 May 2026

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Citation: Alireza R Azadi, Omid Panahi. Artificial Intelligence and Robotic Surgery in Transcrestal Sinus Floor Elevation with Simultaneous Implant Placement: A Near-Future Paradigm. Journal of Dentistry and Oral Health 3(1). https://doi.org/10.61615/JDOH/2026/MAY027140521

Abstract

Transcrestal sinus floor elevation (TSFE) with simultaneous implant placement is a technically demanding procedure used to address posterior maxillary bone deficiency. Traditional techniques rely heavily on tactile feedback and operator experience, with risks including Schneiderian membrane perforation, inaccurate implant positioning, and unpredictable graft outcomes. This article examines how artificial intelligence and robotic surgical systems are converging to transform TSFE into a precise, predictable, and safer procedure. AI contributes through automated preoperative planning, CBCT segmentation, surgical approach classification, and postoperative volumetric graft analysis. Robotic systems provide haptic feedback, force-controlled drilling, and sub-millimeter accuracy. Recent clinical evidence demonstrates that robotic-assisted TSFE achieves a mean apical deviation of 0.56–0.78 mm and angular deviation of 1.38–2.20°, with membrane perforation rates approaching zero. Force-feedback technology enables real-time detection of sinus floor microfracture, transforming a traditionally "blind" procedure into a visually and mechanically monitored operation. The near future will see integrated AI-robotic platforms that autonomously classify surgical needs, execute osteotomies, and quantify graft stability with the surgeon transitioning from operator to supervisor.

Keywords: Transcrestal Sinus Floor Elevation, Simultaneous Implant Placement, Robotic Dental Surgery, Artificial Intelligence, Force Feedback, Schneiderian Membrane, CBCT Segmentation.

Introduction

The Clinical Challenge of the Posterior Maxilla

The posterior maxilla presents a unique challenge in implant dentistry. Following tooth loss, pneumatization of the maxillary sinus, combined with alveolar ridge resorption, frequently results in insufficient bone height for conventional implant placement. Studies indicate that 33.3% to 54.2% of patients require maxillary sinus augmentation prior to or concurrent with implant placement. This anatomical limitation has driven the development of sinus floor elevation techniques over the past four decades **[1-26]**.

Transcrestal sinus floor elevation (TSFE), also known as the osteotome technique or internal sinus lift, was introduced by Summers in 1994. The procedure involves accessing the sinus cavity through the alveolar crest, elevating the Schneiderian membrane, placing graft material, and simultaneously inserting a dental implant through a single osteotomy site. Compared to the lateral window approach, TSFE offers reduced morbidity, shorter healing time, and less patient discomfort **[27-48]**.

Limitations of Traditional TSFE

Despite its advantages, traditional TSFE has significant limitations:

- Blind nature: The surgeon cannot directly visualize the sinus membrane during elevation
- Tactile dependence: Success relies entirely on the surgeon's perception of resistance changes
- Membrane perforation risk: Reported rates range from 3% to 35%, depending on membrane thickness and anatomy
- Inaccurate implant positioning: Freehand placement achieves mean angular deviations of 5-8°
- Operator-dependent outcomes: Significant variability between experienced and novice surgeons

The Technological Solution

The convergence of artificial intelligence and robotic surgery offers a transformative solution to these limitations. AI enables objective preoperative planning, automated anatomical segmentation, and quantitative graft analysis. Robotics provides haptic guidance, force-controlled drilling, and real-time feedback. Together, they address the fundamental limitations of traditional TSFE: unpredictability, imprecision, and operator dependence **[49-67]**.

This article examines the current evidence, technical principles, and near-future trajectory of AI-integrated robotic systems for TSFE with simultaneous implant placement.

AI in Preoperative Planning for TSFE

Artificial Intelligence for Preoperative Planning

Successful TSFE begins with accurate preoperative planning. AI has demonstrated remarkable capabilities in automating and standardizing this critical phase.

Automated CBCT Segmentation

The first step in planning TSFE is precise segmentation of relevant anatomical structures: the maxillary sinus, the Schneiderian membrane (indirectly visualized), residual alveolar bone, and the planned implant position. Manual segmentation is time-consuming (22–50 minutes per case) and subject to inter-operator variability **[68-79]**.

Recent deep learning approaches have transformed this process. A fully automated system named SA-ai, integrating a 2D U-Net for sinus contour detection and a 3D V-Net for maxilla segmentation, achieved a Dice coefficient of 93.2% and registration root mean square error of 1.046 mm. Clinical validation against manual measurements showed excellent agreement for bone volume (Intraclass Correlation Coefficient = 0.993), with workflow efficiency improving over 20-fold compared to manual methods **[80-95]**.

Even more impressive is the system's ability to handle one-stage (simultaneous implant and graft) cases, a population previously excluded from automated analysis due to metal implant artifacts. The SA-ai system incorporates a specialized post-processing workflow that determines net bone gain by excluding implant-occupied space.

Automated Classification of Surgical Approach

Determining whether a patient requires TSFE, lateral window, or alternative bone augmentation is a critical decision. The ABC sinus augmentation classification, developed by Hom-Lay Wang, categorizes residual bone height into: Class A (>10 mm, direct implant placement), Class B (6–9 mm, TSFE appropriate), and Class C (≤5 mm, lateral window indicated) **[96-105]**.

Researchers have developed SinusC-Net, a deep learning model that automatically classifies surgical approaches using a 3D distance-guided network on CBCT images. The model achieves:

- Mean accuracy: 97%
- Sensitivity: 92%
- Specificity: 98%
- Area under curve: 0.95

Five anatomical landmarks, the alveolar crest, sinus floor, medial/lateral horizontal bone width points, and cementoenamel junction, are automatically detected with a mean registration error of 0.87 mm. This automated classification system eliminates subjective variation between clinicians and ensures consistent application of evidence-based treatment algorithms **[106-122]**.

Prediction of Adjunctive Procedure Necessity

A 3D convolutional neural network (3D-CNN) model has been developed to predict the need for adjunctive procedures such as guided bone regeneration or maxillary sinus elevation prior to implant placement. The optimized model achieves an accuracy of 81% with an area under the curve of 79%, demonstrating strong discriminative capabilities.

Robotic Systems for TSFE Execution

Robotic Computer-Assisted Implant Surgery for TSFE

Robotic computer-assisted implant surgery (r-CAIS) represents the most significant advancement in TSFE execution since the original technique description.

Technical Principles of r-CAIS for TSFE

The r-CAIS workflow for TSFE with simultaneous implant placement consists of:

Phase 1: Preoperative Planning

- CBCT acquisition with fiducial markers
- Virtual sinus elevation and stepwise drilling plan creation
- Implant size, position, and trajectory definition

Phase 2: Intraoperative Registration

- Calibration of markers to the robotic arm coordinate system
- Verification of registration accuracy

Phase 3: Robotic Execution

- Robotic arm automatically executes drilling tasks
- Haptic feedback guides osteotomy preparation
- Sinus floor elevation with real-time force monitoring
- Implant placement under robotic guidance

Phase 4: Validation

- Immediate postoperative CBCT
- Deviations measured between planned and actual placement

Accuracy Evidence: Case Series Data

Multiple retrospective case series have evaluated r-CAIS for TSFE. A study by Li and colleagues (2025) included 14 implants in 10 patients with posterior maxillary edentulism **[123-145]**. Results demonstrated:

Parameter Mean Value Range 95% CI

Global coronal deviation 0.72 mm 0.32–1.57 mm 0.52–0.92 mm

Global apical deviation 0.78 mm 0.33–1.50 mm 0.60–0.96 mm

Angular deviation 2.20° 0.16–8.70° 0.82–3.60°

No immediate or significant complications were noted, and no evidence of tissue perforation or premature implantation failure was documented.

A separate evaluation of r-CAIS for TSFE by another research group (2025) reported even higher precision:

- Mean global coronal deviation: 0.55 ± 0.20 mm
- Mean global apical deviation: 0.56 ± 0.23 mm
- Mean angular deviation: 1.38 ± 0.83°

Critically, no membrane perforation was observed during or after surgery in this cohort.

Comparison with Freehand and Static Navigation

These accuracy figures represent substantial improvement over traditional approaches. Freehand implant placement in the posterior maxilla typically achieves angular deviations of 5-8°. Static computer-guided surgery improves this to 2-4°. Robotic systems consistently achieve 1-2° angular deviation, a clinically meaningful difference when anatomy provides minimal margin for error **[146-170]**.

Force-Feedback Technology – Mechanical Vision

Force-Feedback and Mechanical Vision in TSFE

Perhaps the most transformative innovation in robotic TSFE is the integration of force-feedback technology, which effectively creates "mechanical vision" for a traditionally blind procedure.

The Problem of Blind Elevation

Traditional TSFE relies on the surgeon's tactile perception through an osteotome or drill. The surgeon feels resistance as instruments approach the sinus floor, senses a "give" when membrane elevation occurs, and hopes that perforation has not occurred. This dependence on subjective tactile interpretation is a primary source of variability and risk.

Force-Feedback Curves as Mechanical Vision

Recent research has characterized the force-feedback patterns observed during robotic TSFE with osseodensification drilling. The force-feedback curve (specifically Fz, the vertical force component) shows three characteristic phases:

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Phase 1: Cortical Approach

- Force gradually increases as the drill approaches the sinus floor
- Magnitude correlates with cortical bone density at the sinus floor

Phase 2: Microfracture Point

- A critical peak in force is observed
- This is immediately followed by a sharp drop in the "breakthrough" signal
- The system can detect this transition in real-time, alerting the surgeon **[171-185]**

Phase 3: Membrane Elevation

- Force rises gradually as the graft material enters the sinus cavity
- A subsequent steep decrease confirms successful elevation without perforation

Clinical Significance of Real-Time Force Monitoring

The clinical implications are profound. Instead of relying on subjective sensation, the surgeon observes an objective force curve on a screen. When the characteristic peak-drop pattern appears, the surgeon knows precisely when the sinus floor has been breached and that the membrane remains intact. If the force curve shows an abnormal pattern (e.g., sudden drop without preceding peak, or erratic fluctuations), perforation may have occurred, and the surgeon can immediately adjust technique **[186-195]**.

A 2025 study of 18 implants placed using force-feedback robotic TSFE reported a 94.4% implant retention rate at 6 months postoperative. Cortical bone density at the sinus floor positively correlated with force feedback magnitude ($p < 0.05$), enabling preoperative prediction of required force.

AI for Postoperative Graft Volume Analysis

AI-Driven Postoperative Assessment

The surgical procedure is only half the story. Long-term success depends on graft material stability, bone remodeling, and osseointegration. AI is transforming postoperative assessment from subjective estimation to quantitative precision.

The Challenge of Graft Volume Measurement

Accurate assessment of bone graft material changes after TSFE is crucial for evaluating long-term implant survival. Traditional manual labeling and segmentation of CBCT images are inaccurate (inter-operator variability 10-20%) and inefficient (average 1,390 seconds per case).

Deep Learning for Graft Segmentation

Swin-UPerNet, a transformer-based deep learning architecture, has been specifically trained and validated for automated graft material segmentation in one-stage sinus lift procedures. Comparative performance on a test set of 30 CBCT scans:

Model	Accuracy	Precision	IoU
Swin-UPerNet	0.84	0.8574	0.7373
U-Net	—	—	Lower
DeepLabV3	—	—	Lower
SegFormer	—	—	Lower
FCN	—	—	Lower

All differences were statistically significant ($p < 0.05$). Most importantly, the processing time decreased from 1,390 seconds (manual) to just 19.28 seconds with Swin-UPerNet a 72-fold improvement.

Longitudinal Monitoring with the Subtraction Paradigm

The SA-ai system introduces an innovative registration-subtraction paradigm for longitudinal graft monitoring. Instead of directly segmenting graft material, a challenging task due to density changes and domain shift over time, the system:

1. Segments the pre-operative maxilla (T0)
2. Segments the post-operative maxilla containing graft (T1, T2, etc.)
3. Registers the two scans with sub-millimeter accuracy
4. Subtracts the pre-operative volume to isolate the graft

This approach achieves an Intraclass Correlation Coefficient of 0.986 for bone volume measurement, essentially identical to the manual gold standard, but with perfect repeatability and no operator fatigue **[196-204]**.

Integrated AI-Robotic Workflow for TSFE

The Near-Future Clinical Workflow

The convergence of AI planning, robotic execution, and AI postoperative analysis enables a fully integrated digital workflow for TSFE with simultaneous implant placement.

6.1 Phase 1: AI-Driven Planning (Preoperative, Day -7 to Day -1)

Input: CBCT scan (acquired with fiducial markers)

AI Actions

- Automated segmentation of maxillary sinus, residual ridge, and adjacent anatomy (SA-ai system; 93.2% Dice coefficient)
- Automatic classification of surgical approach (SinusC-Net; 97% accuracy)
- Prediction of RBH and bone quality parameters (3D-CNN; 81% accuracy)
- Generation of implant size, position, and trajectory proposals
- Virtual simulation of sinus elevation and graft volume requirements

Human Surgeon Role: Review and approve AI-generated plan; modify if clinical factors warrant.

Phase 2: Robotic Execution (Operative Day)

Robotic Actions

- Automated registration of markers to robotic arm coordinates
- Force-controlled osteotomy preparation with real-time feedback
- Detection of sinus floor breach via force-curve analysis (mechanical vision)
- Controlled membrane elevation and graft material delivery
- Simultaneous implant placement with haptic guidance

Human Surgeon Role: Supervise robotic execution; maintain sterile field; manage soft tissue retraction; verify implant position; respond to emergency overrides.

Expected Outcome: Apical deviation ≤ 0.8 mm; angular deviation ≤ 2.0°; zero membrane perforation.

Phase 3: AI-Postoperative Assessment (Immediate and Long-term)

Input: Postoperative CBCT (immediate, 6 months, 12 months)

AI Actions

- Registration of pre- and post-operative scans (RMSE 1.046 mm)
- Quantification of graft volume, dimensional stability, and remodeling
- Detection of complications (e.g., graft migration, sinus pathology)
- Prediction of implant stability based on graft integration metrics

Human Surgeon Role: Interpret AI reports; correlate with clinical examination; plan prosthetic phase **[205-215]**.

Remaining Limitations and Challenges

Barriers to Widespread Adoption

Despite compelling evidence, several barriers must be addressed before integrated AI-robotic TSFE becomes standard of care.

Cost and Accessibility

Robotic systems for implant surgery currently cost $150,000–$400,000, placing them beyond the reach of solo practitioners and small clinics. However, dental service organizations (DSOs) and academic centers are increasingly adopting these systems, and subscription-based models may reduce the entry barrier.

Learning Curve for Technology Adoption

Surgeons trained in traditional techniques must learn new workflows: marker placement, registration verification, force-curve interpretation, and emergency override procedures. Fortunately, the learning curve appears relatively shallow; the largest case series report consistent accuracy from the first case.

The "Domain Shift" Problem for AI Segmentation

Deep learning models trained on immediate postoperative data may experience performance degradation when applied to scans taken 6 or 12 months later, as graft material density, texture, and morphology change during remodeling. The registration-subtraction paradigm addresses this partially, but longitudinal validation across diverse patient populations is still needed.

Evidence Gaps

Current evidence is limited to retrospective case series with modest sample sizes (10–17 patients). Prospective randomized controlled trials comparing robotic TSFE to freehand and static navigation are urgently needed. Long-term (5+ years) implant survival data for robotic-placed implants in grafted sinuses is not yet available.

Systematic Overestimation in Automated Methods

AI-based volumetric analysis of bone grafts shows systematic overestimation (mean percentage error 9.86%) compared to manual measurement. While automated methods demonstrate higher precision (lower standard deviation), the systematic bias means they should be used with caution in studies requiring faithful estimation of biological volume.

A Scenario for 2030

The Integrated Clinic of 2030: A Day in the Life

Time: 9:00 AM.

Dr. Peterson reviews the day's first case through the clinic's AI dashboard. Patient Mrs. Chen, age 58, requires implant #15. Residual bone height is 6.5 mm, Class B, appropriate for TSFE.

Phase 1 – Planning (Completed prior to appointment)

The AI system (SA-ai) automatically segmented her pre-op CBCT, calculated precise RBH, and proposed an implant 10 mm in length, 4.3 mm in diameter. SinusC-Net classified the surgical approach as "B" (TSFE with simultaneous implant). Dr. Peterson reviewed and approved the plan in 90 seconds **[216-218]**.

Phase 2 – Execution

Mrs. Chen is seated. The robotic arm, pre-calibrated to her fiducial markers, moves into position. Dr. Peterson places the initial pilot drill in the handpiece. The robot provides haptic resistance, preventing any deviation from the planned trajectory.

As the osteotomy approaches the sinus floor (depth 6.5 mm), the force-feedback display shows the characteristic curve: a steady rise, then a peak, then a sharp drop. "Microfracture detected," the system announces. The robot automatically stops forward progress. Dr. Peterson switches to the elevation instrument. The robot guides it to the exact microfracture point.

Graft material (xenogeneic) is delivered through the robotic sleeve. The implant is placed under robotic guidance. Total robotic operative time: 14 minutes.

Phase 3 – Confirmation

Immediate postoperative CBCT is acquired. The AI system registers pre- and post-operative scans. Apical deviation: 0.51 mm. Angular deviation: 1.2°. Graft volume: 0.28 cc. The report is automatically added to Mrs. Chen's electronic health record.

Outcome: Mrs. Chen's implant is placed with precision exceeding freehand standards by a factor of 4-5x. Her risk of membrane perforation is statistically near zero. Dr. Peterson performed the procedure with less mental fatigue than a traditional TSFE, focusing on patient interaction and supervision rather than precision micromotor control.

Conclusion

The integration of artificial intelligence and robotic surgery into transcrestal sinus floor elevation with simultaneous implant placement represents a paradigm shift in posterior maxillary implantology.

Summary of Evidence

Current evidence from multiple retrospective case series demonstrates that r-CAIS for TSFE achieves:

- Sub-millimeter accuracy: Apical deviation 0.56–0.78 mm
- Excellent angular control: Angular deviation 1.38–2.20°
- Near-zero perforation rates: No membrane perforations reported in recent series
- Objective force monitoring: Real-time detection of microfracture through mechanical vision
- Automated planning and analysis: AI systems achieving 93%+ Dice coefficients and 72x efficiency improvements

The Changing Role of the Surgeon

The surgeon's role in TSFE is evolving from operator to supervisor. The premium skills shift from tactile sensitivity and manual dexterity to:

- Critical evaluation of AI-generated surgical plans
- Interpretation of force-feedback data
- Recognition of when to override robotic automation
- Integration of quantitative AI reports with clinical judgment

The Near-Future Trajectory (2026–2030)

Within five years, we can expect:

1. Regulatory approval of fully autonomous (conditional autonomy, Level 3) systems for TSFE in select indications
2. Subscription-based pricing models reduce the capital barrier to entry
3. Prospective RCTs providing Level 1 evidence for robotic TSFE superiority
4. Integration of intraoperative AI for real-time adaptation to unexpected anatomy
5. Standardization of AI reporting for graft volume quantification across implant centers

Final Statement

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The question is no longer whether AI and robotics will transform TSFE with simultaneous implant placement, but how quickly this transformation will disseminate into routine clinical practice. For the patient, the promise is precise, predictable, and safer surgery. For the surgeon, the promise is reduced physical demands, objective feedback, and enhanced outcomes. For the profession, the promise is standardization of a technically demanding procedure, making high-quality sinus elevation available to more patients under the care of more clinicians.

The traditional TSFE, dependent on blind tactile estimation, is being replaced by a data-driven, visually monitored, force-controlled robotic procedure. The future of sinus augmentation is not human versus machine, but human amplified by machine.

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Citation: Alireza R Azadi, Omid Panahi. Artificial Intelligence and Robotic Surgery in Transcrestal Sinus Floor Elevation with Simultaneous Implant Placement: A Near-Future Paradigm. Journal of Dentistry and Oral Health 3(1).
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