

Evaluating computer-assisted mandibular reconstruction: Outsourced vs. in-house approaches

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Abstract. Mandibular reconstruction following segmental resection, often necessitated by oral malignancies, is a complex procedure that markedly affects postoperative function and aesthetics. Computer-assisted surgery (CAS) has emerged as a valuable tool for enhancing surgical precision in oncological head and neck reconstruction. The present study evaluated the accuracy of mandibular reconstruction using three approaches: Conventional (non-CAS), outsourced CAS (TruMatch) and an in-house CAS system developed at The University of Osaka Graduate School of Dentistry (Suita, Japan). A total of 32 cases, predominantly involving malignant tumors, were retrospectively analyzed using three-dimensional model overlay techniques to compare pre- and postoperative outcomes. While both CAS methods significantly improved accuracy compared with the non-CAS approach, no statistical difference was found between the outsourced and in-house CAS groups. These findings suggested that in-house CAS systems can achieve comparable precision to commercial solutions, offering a cost-effective and accessible alternative for advanced mandibular reconstruction in oncology settings. The results support broader adoption of in-house CAS approaches, particularly in time-sensitive or resource-limited cancer surgeries.

Introduction

Mandibular reconstruction following segmental resection, often performed in the context of oral and maxillofacial

malignancies, is one of the most challenging procedures in head and neck oncology. The accuracy of reconstruction critically affects postoperative oral function, facial symmetry, and overall quality of life. Due to both cosmetic and functional considerations, including the maintenance of occlusion, mandibular reconstruction requires precise alignment and preservation of the spatial relationship between the divided bone fragments pre- and postoperatively. After segmental mandibular resection, the bone may be replaced with a graft, and various bone sources have been used, including the fibula, iliac crest, scapula, and radius of the forearm. When using bone replacements, sculpting them precisely to fit the mandibular defect intraoperatively and aligning them optimally to enhance bone approximation and promote bone healing is crucial (1-4).

Traditionally, mandibular reconstruction has relied on free-hand techniques, which are highly dependent on the surgeon's experience and intraoperative judgment. These methods often result in variability in outcomes and prolonged surgical time. Computer-assisted surgery (CAS) for mandibular reconstruction has been increasingly adopted in clinical practice. CAS encompasses a surgical approach and a set of methods that use computer technology for surgical planning, guidance, or execution of interventions. CAS in mandibular reconstruction was first implemented clinically by determining the extent of mandibular resection, the shape of the mandibular reconstruction metal plate, and the morphology and position of the graft bone through preoperative computer simulation, as described by Hirsch *et al* in 2009 (1). The resulting three-dimensional (3D)-printed osteotomy guides and preshaped mandibular reconstruction plates allow precisely planned surgery to be executed with high accuracy and greater efficiency in the operating room. These advancements reduce surgical duration and facilitate technique optimization (2,5-15).

Currently, outsourced mandibular reconstruction CAS systems, such as TruMatch® (DePuy Synthes, MA, USA), are widely used (16). Introduced in Japan in 2022, the TruMatch system has been applied in numerous cases at our facility. However, these systems require long preparation times, typically one month, and incur substantial costs, which may limit their accessibility, especially in urgent oncologic cases. Additionally, communication with external engineers during

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planning may not fully capture the surgeon's intent, and the hospital receives only the final product, with limited control over the design process (17). To overcome these challenges, we developed an in-house CAS system utilizing widely available 3D printing and surgical simulation software. This system allows for rapid planning, greater customization, and reduced costs, making it a potentially viable alternative to commercial solutions. Despite the growing interest in in-house CAS, few studies have directly compared its accuracy with that of outsourced systems or conventional methods.

Therefore, this study aimed to evaluate and compare the accuracy of mandibular reconstruction using three approaches: conventional surgery (non-CAS), outsourced CAS (TruMatch), and an in-house CAS system. Given that the majority of cases involved segmental mandibulectomy for malignant tumors, particularly oral cancer, the study also sought to assess the feasibility and precision of CAS-based reconstruction in oncologic settings. Postoperative outcomes were analyzed using 3D model overlay techniques to determine whether in-house CAS could provide accuracy comparable to that of outsourced systems and support broader clinical application in cancer-related mandibular reconstruction.

Materials and methods

Patients. All patients who underwent mandibular reconstruction surgery at our department (Center for Oral Cancer, The University of Osaka Dental Hospital, Suita, Japan) between April 2018 and January 2025 were included in this study. The cases were categorized into three groups based on the surgical technique and time period:

Non-CAS group: Cases treated before March 2021, prior to the introduction of CAS at our institution. These cases were managed using conventional freehand techniques with mini-plates. In cases where the mandibular segment would have been too small following resection, segmental reconstruction was not feasible, and a hemimandibulectomy was performed instead.

Outsourced CAS (TruMatch) group: Cases treated after March 2021, where sufficient preparation time (≥ 1 month) and budget permitted the use of outsourced CAS. TruMatch was not used in urgent cases or when financial constraints precluded outsourcing.

In-house CAS group: Cases treated after August 2022, where outsourced CAS was not feasible due to time or cost limitations. These cases underwent preoperative simulation and guide design using Vincent and 3Shape software within our institution. Standard reconstruction plates were manually contoured to fit the simulated mandibular model and positioned intraoperatively using custom-designed devices. The scapular graft was adjusted and fixed in the same manner as in the TruMatch group.

However, we excluded cases where one mandibular condyle was completely resected and thus could not be analyzed, cases where the reconstruction plate was temporarily positioned directly on the mandible prior to resection during surgery, and cases where pre- and postoperative computed tomography (CT) scans were unavailable for comparison. All surgeries were performed by a consistent surgical team specializing in oral and maxillofacial oncology. The principal

surgeons were board-certified oral and maxillofacial surgeons with over 10 years of clinical experience in oncologic head and neck surgery. The core members of this team remained unchanged throughout the study period, thereby minimizing variability related to surgeon experience. Of the 59 cases of segmental mandibular resection performed during this period, 32 were included in this study. This retrospective study was approved by the Institutional Review Board of The University of Osaka Graduate School of Dentistry (approval number: R6-E35). Although all patients were treated at The University of Osaka Dental Hospital, ethics approval was obtained from the university-level committee in accordance with institutional policy. At The University of Osaka Graduate School of Dentistry, retrospective clinical studies involving comparative analysis of multiple cases, including those using opt-out consent, require formal review and approval by the Graduate School of Dentistry Research Ethics Committee to ensure consistent ethical oversight across affiliated institutions. Patient data were collected from electronic medical records and imaging archives maintained at The University of Osaka Dental Hospital. In accordance with ethical guidelines, informed consent was obtained from all patients using an opt-out method, whereby information about the study was disclosed publicly and patients were given the opportunity to decline participation. The University of Osaka Dental Hospital is officially affiliated with The University of Osaka Graduate School of Dentistry.

Virtual surgical planning and 3D fabrication of surgical devices. All patients underwent CT scans of the mandible. Similarly, patients planned for scapular grafting underwent scapular CT imaging. The CT scans were saved as Digital Imaging and Communications in Medicine files, segmented, and converted into a virtual 3D model in Stereolithography (STL) format. For cases using the TruMatch (DePuy Synthes, MA, USA) system, the order was placed at least 1 month prior to surgery and discussed with the company technician during preoperative planning. For the in-house CAS system, a virtual mandibulectomy and reconstruction of the planned mandibular defect were performed using Vincent software (Fujifilm, Japan), which allowed for interactive 3D modeling of the mandible and donor bone. Cases with severely deformed mandibles due to tumors, fractures, or segmental defects were modeled based on the contralateral, unaffected side using the mirror image principle (8,12,18). The cutting guide and bone/plate-positioning devices were designed using Vincent software and the 3Shape Dental System (3Shape, Denmark) (Fig. 1). The 3D models of the mandible, bone/plate-positioning devices, and cutting-guide devices were fabricated in photopolymer resin using a 3D printer (Formlabs Inc., MA, USA). A 3D-printed model of the reconstructed mandible was created. Preoperatively, a 2.6-mm locking titanium mandibular reconstruction plate was manually contoured to fit the 3D-reconstructed mandibular model.

Vincent software, originally developed as a diagnostic imaging viewer and analysis tool for radiology, is primarily used to evaluate CT and magnetic resonance imaging data and does not include surgical simulation functions by default. In this study, we adapted the Vincent software for virtual mandibulectomy and 3D modeling by utilizing its

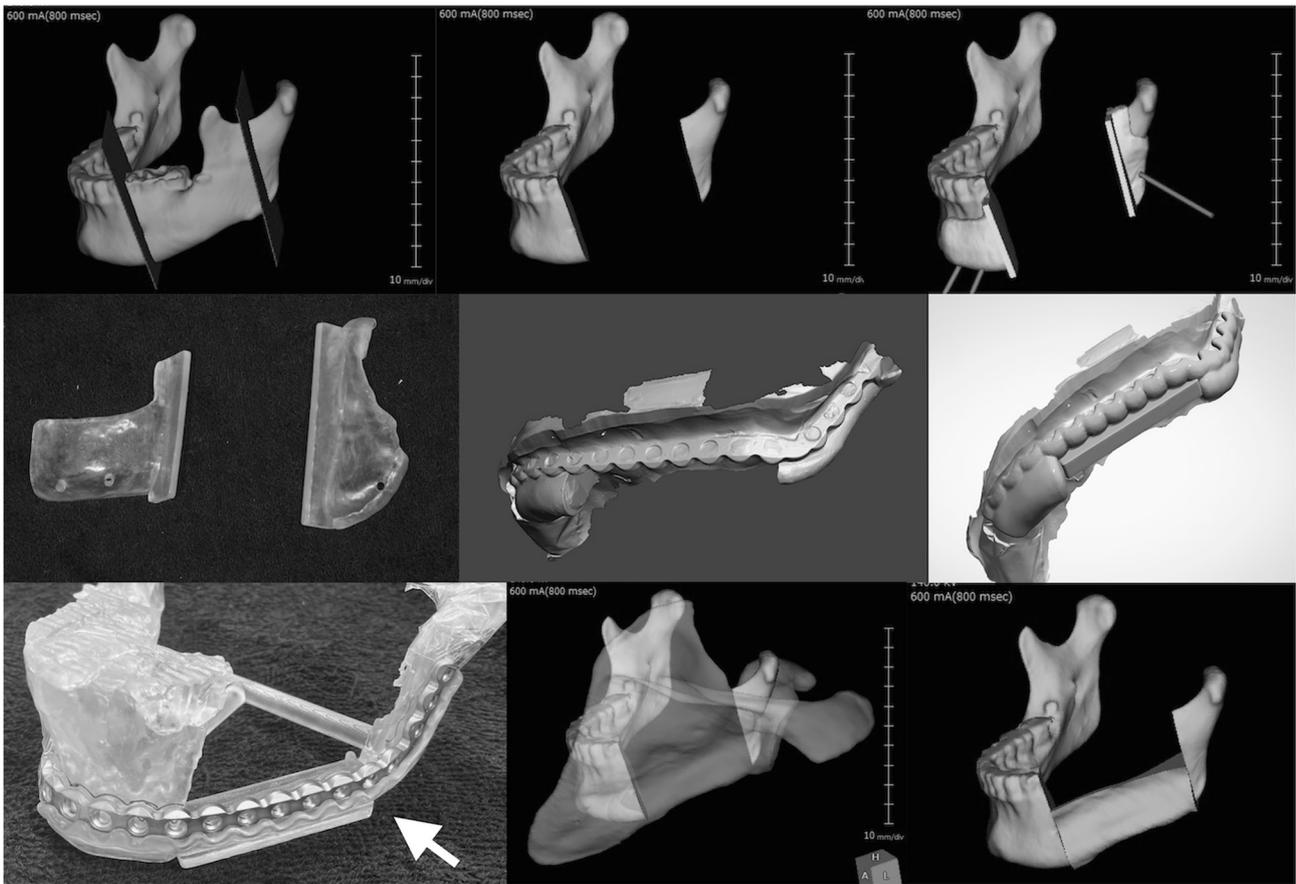


Figure 1. The design image of the in-house computer-assisted surgery system for mandibular reconstruction. Although this system requires the use of a ready-made reconstruction plate, the bone/plate-positioning device (arrow) is essential for accurate placement.

segmentation and visualization capabilities. The 3Shape Dental System, primarily intended for designing dental prostheses such as crowns, bridges, custom impression trays, and complete or partial dentures, was repurposed in our workflow. Specifically, we employed its CAD modules to design bone and plate positioning devices for mandibular reconstruction.

Surgical procedure. The surgeries were broadly divided into the following three types: non-CAS, TruMatch, and in-house CAS (Figs. 2-4). In non-CAS, intermaxillary fixation was used to maintain the mandible's position after amputation, or a positioning plate was used to fix it to the maxilla.

Accuracy analysis. Postoperative CT scans were taken approximately 1 month after surgery in all cases. These scans were used for accuracy assessment through 3D model overlay analysis. The postoperative CT scans were converted into 3D-STL models, which were then superimposed on the preoperative 3D-STL models used for virtual surgical planning, with the apex of the mandibular condyle serving as the anchor point (software: Vincent, Fujifilm). The discrepancy between the planned and actual mandibular reconstruction was evaluated using two metrics: the intercondylar distance (ICD, defined as the change in linear distance between the apices of the bilateral mandibular condyles before and after surgery, as described by Zhang *et al*) (19) and the 3D deviation distance (3DD, defined as the spatial deviation of

the apex of the affected mandibular condyle between the planned and actual postoperative positions) (Fig. 5). The analysis was performed using Vincent software (Fujifilm, Japan) as follows: A single anatomical landmark, the apex of the mandibular condyle, was defined as the most superior point of the condyle on the preoperative CT scan. Using Vincent's overlay function, the postoperative condyle was superimposed onto the preoperative condyle for each side separately, and the same apex point was defined at the postoperative condyles. Next, using the healthy side of the mandible (including the mandibular body, angle, and ramus) as a reference, the preoperative and postoperative models were overlaid again using Vincent's overlay function. Based on this 3D overlay, the ICD was calculated as the difference in ICD before and after surgery, and the 3DD was calculated as the spatial deviation of the affected condyle apex.

Statistical analysis. To determine the appropriate statistical tests, we assessed the normality of the ICD and 3DD datasets using the Shapiro-Wilk test. Based on the results and the limited sample size, comparisons among the three groups were conducted using the Kruskal-Wallis test, followed by Dunn's multiple comparisons test. However, the comparison between two groups was analyzed using the Mann-Whitney U test. Statistical analyses were performed using GraphPad Prism version 10 (GraphPad Software, CA, USA). $P < 0.05$ was considered to indicate a statistically significant difference.

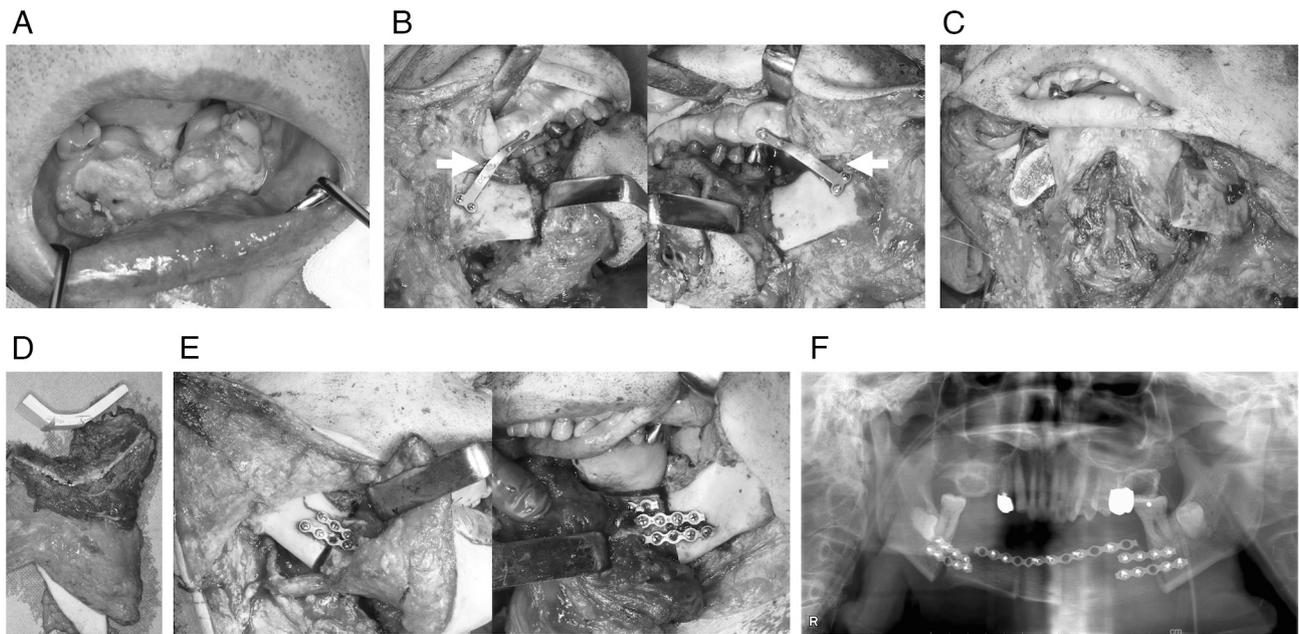


Figure 2. Intraoperative images of mandibular reconstruction using the non-computer-assisted surgery system. (A) Intraoral image before surgery. (B) Attaching the mandibular positioning plate (arrows). (C) After resection of the mandible. (D) Adjustment of the scapula graft. (E) After scapula graft fixation. (F) Postoperative panoramic radiograph.

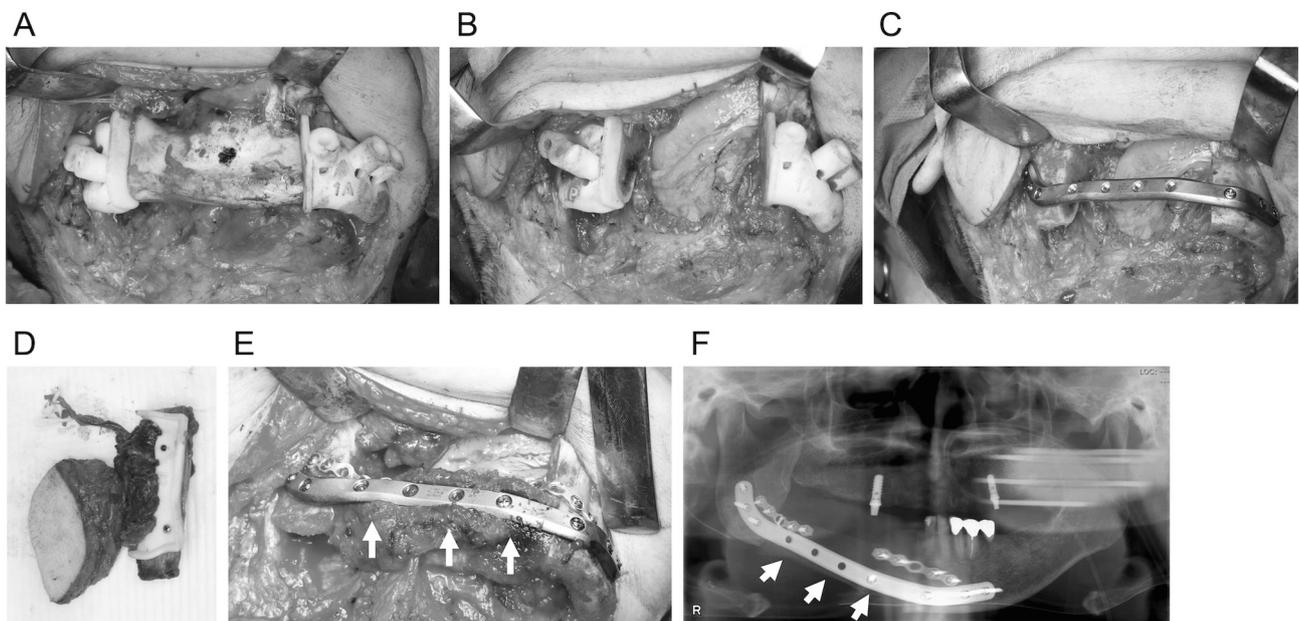


Figure 3. Intraoperative images of mandibular reconstruction using the TruMatch system. (A) Placement of cutting guide devices, which also function as drilling guides for the TruMatch plate. (B) After resection of the mandible. (C) After placement of the TruMatch plate. (D) Adjustment of the scapula graft. (E) After scapula graft fixation (arrows). (F) Postoperative panoramic radiograph (arrows: the TruMatch plate and the grafted scapula).

Results

Between April 2018 and January 2025, a total of 32 cases were included, comprising eight non-CAS cases, 13 TruMatch cases, and 11 in-house CAS cases (Tables I-III). The overall mean age of patients was 67.8 years, with 13 females and 19 males. Of the 32 cases, 23 involved malignant tumors, eight involved benign tumors, and three were cases of osteomyelitis. Regarding mandibular reconstruction, five cases involved

plate-only reconstruction, eight cases involved plate + pectoralis major myocutaneous flap, 16 cases involved plate + scapular flap, two cases involved plate + fibula flap, and one case involved plate + rectus abdominis musculocutaneous flap (Table IV). Based on the classification of mandibular defects by Boyd *et al* (HCL classification) (20), nine cases (28.1%) were classified as lateral-condyle (LC) or lateral-condyle-lateral (LCL) mandibular defects. Furthermore, almost all in-house CAS cases involved malignant tumors, and half of these cases

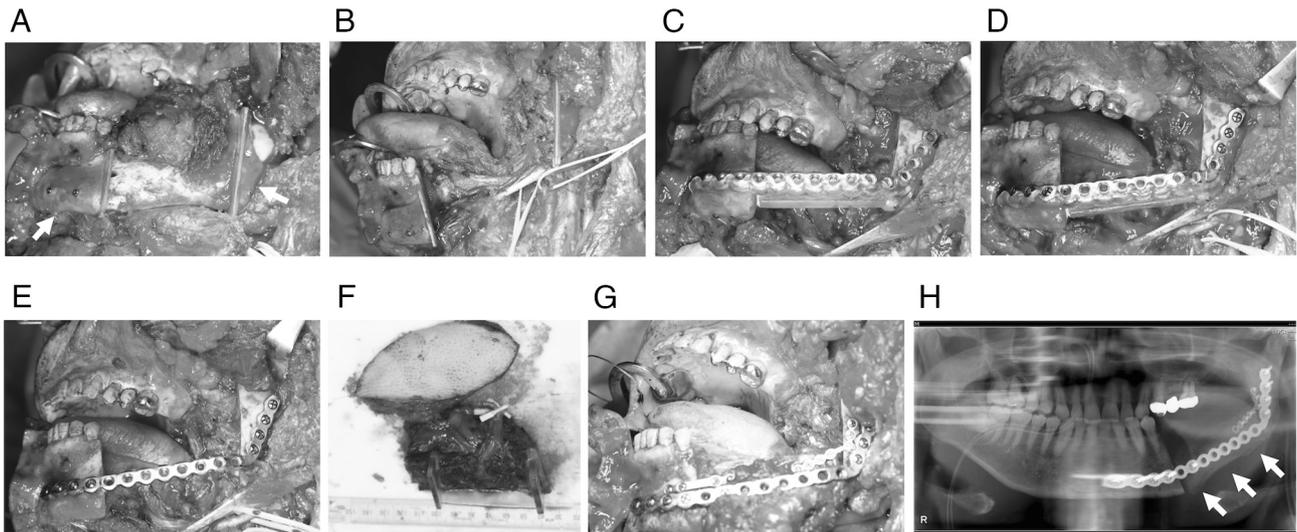


Figure 4. Intraoperative images of mandibular reconstruction using the in-house computer-assisted surgery system. (A) Placement of cutting guide devices (arrows). (B) After resection of the mandible. (C) After placement of the plate and bone/plate-positioning device. (D) After fixation of the plate. (E) After removing the plate positioning device. (F) Adjustment of the scapula graft. (G) After scapula graft fixation. (H) Postoperative panoramic radiograph (arrows: The plate and the grafted scapula).

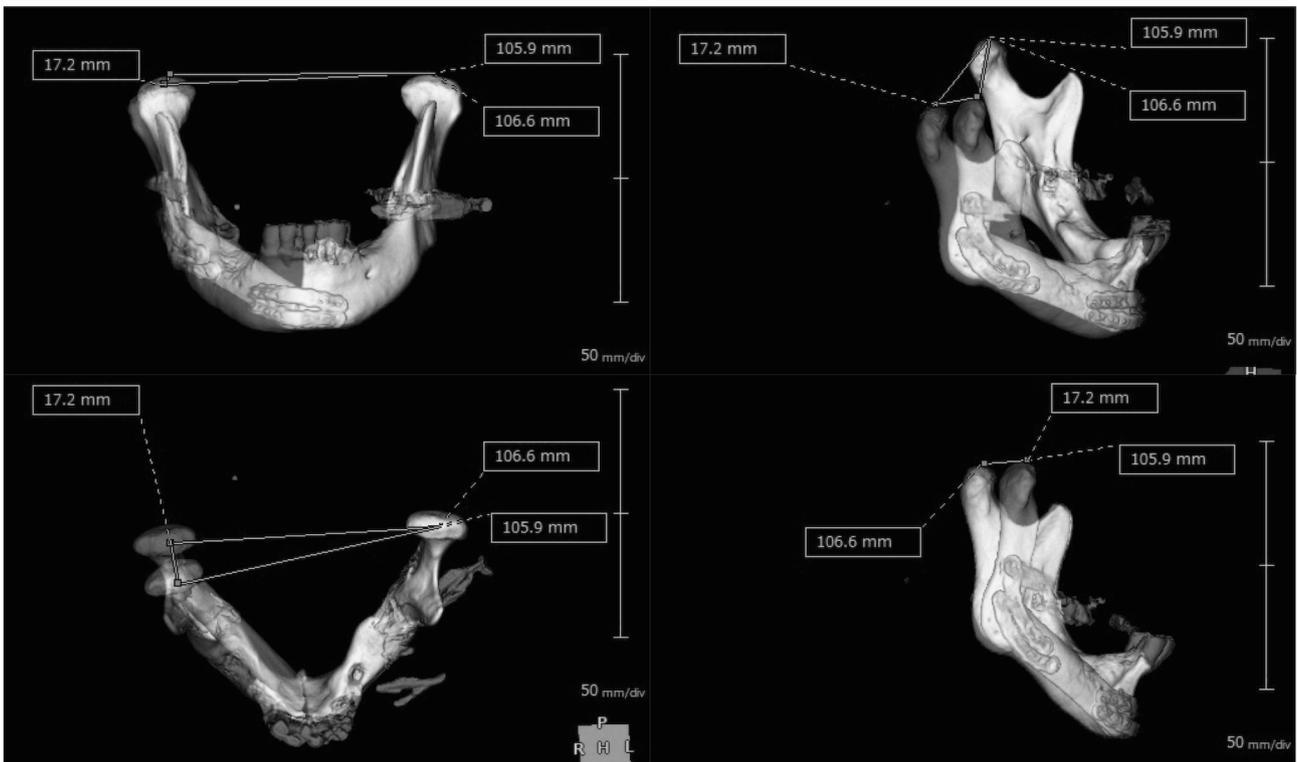


Figure 5. Three-dimensional accuracy analysis for a representative case from the non-computer-assisted surgery group. The analysis results for this case show that the preoperative condylar distance is 106.6 mm, the postoperative condylar distance is 105.9 mm, the intercondylar distance, which indicates the change in the condylar distance, is 0.7 mm, and the 3D deviation distance, which indicates the three-dimensional displacement of the condylar, is 17.2 mm.

were classified as LC or LCL. In both TruMatch and in-house CAS cases, the occlusal relationship was well maintained pre- and postoperatively (Fig. 6).

The results of the accuracy analysis using 3D model overlay comparison are presented in Fig. 7. The ICD measurements were 2.3 mm on average [standard deviation (SD): 3.3] in the non-CAS group, 1.9 mm on average (SD: 1.7) in the TruMatch

cases, and 1.8 mm on average (SD: 1.3) in the in-house CAS group. No significant differences were observed among the three groups. However, the 3DD results were 11.2 mm on average (SD: 7.4) in the non-CAS group, 4.2 mm on average (SD: 2.4) in the TruMatch group, and 5.1 mm on average (SD: 2.7) in the in-house CAS group. The 3DD results indicated that CAS-assisted cases were significantly more accurate, with no significant difference

Table I. List of the non-computer-assisted surgery system cases.

No.	Age, years	Sex	Diagnosis	HCL classification	Reconstruction
1	69	M	Carcinoma of mandibular gingiva	L	Fibula flap, mini-plate
2	37	F	Ossifying fibroma	L	Scapula flap, mini-plate
3	77	F	Carcinoma of mandibular gingiva	LCL	Scapula flap, mini-plate
4	52	F	Ameloblastoma	L	Scapula flap, mini-plate
5	78	M	Carcinoma of floor of mouth	LCL	Scapula flap, mini-plate
6	75	M	Carcinoma of mandibular gingiva	L	Fibula flap, mini-plate
7	65	M	Carcinoma of mandibular gingiva	L	Scapula flap, mini-plate
8	74	M	Carcinoma of mandibular gingiva	L	Scapula flap, mini-plate

F, female; M, male; HCL classification, comprising H (hemimandibular), C (central) and L (lateral) defects.

Table II. List of the TruMatch system cases.

No.	Age, years	Sex	Diagnosis	HCL classification	Reconstruction
1	70	M	Carcinoma of mandibular gingiva	L	TruMatch plate, scapula flap
2	77	M	Radiation osteomyelitis ^a	L	TruMatch plate, PMMC-flap
3	49	F	Ameloblastoma	L	TruMatch plate
4	65	M	Carcinoma of mandibular gingiva	L	TruMatch plate, scapula flap
5	67	M	Carcinoma of mandibular gingiva	L	TruMatch plate, PMMC-flap
6	73	M	Ameloblastoma	L	TruMatch plate
7	71	F	Ameloblastoma	L	TruMatch plate, scapula flap
8	56	F	Carcinoma of mandibular gingiva	L	TruMatch plate, scapula flap
9	65	M	Carcinoma of mandibular gingiva	LCL	TruMatch plate, scapula flap
10	29	F	Cementoblastoma	L	TruMatch plate, scapula flap
11	83	F	Medication-Related Osteonecrosis of the Jaw	LCL	TruMatch plate
12	63	M	Postoperative mandibular gingival carcinoma	L	TruMatch plate, scapula flap
13	77	M	Postoperative mandibular gingival carcinoma	L	TruMatch plate

F, female; M, male; PMMC-flap, pectoralis major myocutaneous flap. ^aCarcinoma of floor of mouth, after surgical operation and radiation; HCL classification, comprising H (hemimandibular), C (central) and L (lateral) defects.

between the TruMatch and in-house CAS groups. However, significant differences were observed between the TruMatch and non-CAS groups (adjusted $P=0.0193$) and between the in-house CAS and non-CAS groups (adjusted $P=0.0499$).

Discussion

This study aimed to evaluate the accuracy of mandibular reconstruction using three approaches: conventional (non-CAS), outsourced CAS (TruMatch), and in-house CAS. The results demonstrated that both CAS methods significantly improved mandibular segment positioning compared with the conventional method, with no significant difference in accuracy between outsourced and in-house CAS.

In conventional mandibular reconstruction, plates are typically pre-bent and temporarily fixed to the mandible before resection to preserve the spatial relationship between bone

segments. However, this technique is feasible only when the bone surface is clearly visible and unaffected by disease. In cases involving tumor-related deformity or indistinct resection margins, preoperative plate fixation is not possible, and attempting it may result in plate protrusion and facial deformity.

All CAS cases in this study were selected because preoperative plate fixation could not be performed. By contrast, the non-CAS group included patients in whom reconstruction plates were not applicable, and miniplates with bone grafts were used instead. This selection strategy ensured that all groups faced comparable surgical challenges regarding mandibular segment positioning. Importantly, the presence or absence of bone grafting does not influence the accuracy of segment alignment, which was the primary focus of this study. This statement is supported by internal data comparing CAS cases with and without bone grafting, which showed no

Table III. List of the in-house computer-assisted surgery system cases.

No.	Age, years	Sex	Diagnosis	HCL classification	Reconstruction
1	94	F	Carcinoma of mandibular gingiva	LC	In-house plate
2	86	F	Carcinoma of mandibular gingiva	LCL	In-house plate, PMMC-flap
3	70	M	Carcinoma of mandibular gingiva	L	In-house plate, scapula flap
4	78	M	Carcinoma of mandibular gingiva	L	In-house plate, PMMC-flap
5	51	M	Carcinoma of mandibular gingiva	LCL	In-house plate, PMMC-flap
6	80	F	Carcinoma of mandibular gingiva	L	In-house plate, PMMC-flap
7	67	F	Carcinoma of mandibular gingiva	LCL	In-house plate, PMMC-flap
8	90	F	Carcinoma of mandibular gingiva	LCL	In-house plate, PMMC-flap
9	58	M	Carcinoma of mandibular gingiva	L	In-house plate, scapula flap
10	55	M	Carcinoma of mandibular gingiva	L	In-house plate, scapula flap
11	70	M	Radiation osteomyelitis ^a	L	In-house plate, RA-flap

F, female; M, male; PMMC-flap, pectoralis major myocutaneous flap; RA-flap, rectus abdominis musculocutaneous flap. ^aCarcinoma of mandibular gingiva, after surgical radiation; HCL classification, comprising H (hemimandibular), C (central) and L (lateral) defects.

Table IV. Patient characteristics.

Characteristic	Total	Non-CAS	TruMatch	In-house
Mean age, years	67.8	65.9	65.0	72.6
Cases	32	8	13	11
Sex				
Female	13	3	5	5
Male	19	5	8	6
Reconstruction				
Only the plate	5	0	4	1
The plate + PMMC-flap	8	0	2	6
The plate + scapula flap	16	6	7	3
The plate + fibula flap	2	2	0	0
The plate + RA-flap	1	0	0	1
Primary disease				
Malignant tumor	23	6	7	10
Benign tumor	6	2	4	0
Osteomyelitis	3	0	2	1
HCL classification				
L	23	6	11	6
LC or LCL	9	2	2	5

CAS, computer-assisted surgery; PMMC-flap, pectoralis major myocutaneous flap; HCL classification, comprising H (hemimandibular), C (central) and L (lateral) defects.

significant difference in either ICD or 3DD (Fig. S1). Therefore, we believe that bone grafting does not affect the spatial positioning of mandibular segments, and the comparison across groups remains valid.

The advantages of using CAS in mandibular reconstruction are as follows: i) the ability to define the resection range precisely by simulating surgery on CT images; ii) the cutting-guide device for the mandible enables accurate and

efficient bone resection; iii) the grafting-bone cutting-guide reduces the preparation time required for bone adjustment; iv) the occlusal relationship can be maintained almost identically to the preoperative condition; and v) custom-made plates eliminate the need for bending, minimizing the risk of plate fracture due to metal fatigue (16,21). However, outsourced custom-made CAS systems also have some limitations. First, they require a preparation period of at least 1 month, making

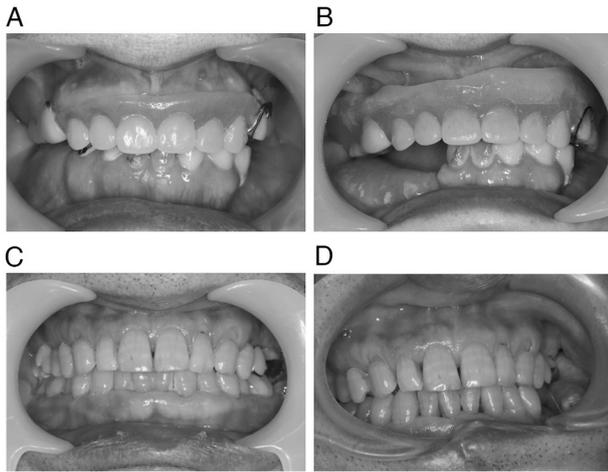


Figure 6. Occlusal relationship in TruMatch and in-house CAS cases. (A) Preoperative occlusal relationship in a TruMatch case. (B) Postoperative occlusal relationship in a TruMatch case. (C) Preoperative occlusal relationship in an in-house CAS case. (D) Postoperative occlusal relationship in an in-house CAS case. CAS, computer-assisted surgery.

them challenging to use in malignant tumor cases. Due to outsourcing, the high costs make it difficult for hospitals to profit, and cancellations can result in significant financial losses. Additionally, since the meetings are held online, it can be difficult for engineers to fully understand the surgeon's specific needs (17). The outsourcing retains all data during the creation process, meaning the hospital only receives the final product. To address these issues, we initiated mandibular reconstruction using our in-house CAS system in 2022. In terms of cost, the outsourced TruMatch system, including the custom plate, screws, surgical guides, and 3D models, typically costs more than ¥800,000 per case in Japan. By contrast, our in-house CAS system costs approximately ¥150,000 per case. This substantial cost reduction is primarily attributed to our institution's ownership of 3D printing equipment and the availability of skilled dental technicians proficient in the software and fabrication process. Although these institutional advantages may not be universally applicable, they demonstrate the potential for cost-effective CAS implementation in facilities with comparable resources.

The reported improvement in efficiency from shortening the operation time is between 80 and 88 min (6,22), and the reduction in free-flap ischemia time is reported to be 36-50 min (19,22). One of the greatest advantages of reconstruction using surgical devices with CAS is that the surgical plan can be easily and rapidly reproduced in the operating room. The learning curve for freehand graft bone sculpting and plate bending without CAS is long, and outcomes vary between surgeons depending on their experience and technical skills (23). CAS, through the use of surgical guides, reduces the learning curve of mandibular reconstruction and significantly enhances proficiency and precision (13,22). Surgical results using surgical guides are consistent and reproducible, even by surgeons with varying levels of experience, which benefits less experienced surgeons (14). In our study, all surgeries were performed by a consistent surgical team specializing in oral and maxillofacial oncology. The core members of this team

remained unchanged across the three groups (non-CAS, outsourced CAS, and in-house CAS), minimizing variability related to individual surgeon experience. However, we acknowledge that other potential confounding factors, such as differences in tumor size, defect classification, and the presence or absence of bone grafting, may have influenced the outcomes. To mitigate this, cases were selected based on a common criterion: the inability to perform preoperative plate fixation due to tumor-related bone deformity or unclear resection margins. Furthermore, internal data comparing CAS cases with and without bone grafting showed no significant difference in ICD or 3DD, suggesting that grafting itself does not affect segment positioning accuracy. These factors support the validity of our comparative analysis.

Several classification systems for mandibular defects have been proposed, with the HCL classification being the most widely used due to its simplicity (20,24). However, it may lack detail in distinguishing functional and reconstructive differences within the same category. In Japan, the CAT classification offers a more detailed framework by using six anatomical landmarks, allowing for better prediction of reconstruction strategies and outcomes (25). Although more complex, it provides clearer guidance for clinical decision-making. In this study, the HCL classification was used for consistency with international standards. Generally, mandibular reconstruction may be more difficult in LC and LCL cases due to mandibular defects in the anterior region compared to cases classified as L. However, this trend was not observed in this study. Although it might be difficult to detect a trend due to the small number of cases, it is possible that when CAS is used, accuracy is not affected even in cases with mandibular defects in the anterior region.

This single-center retrospective study compared the accuracy of reconstruction using CAS vs. non-CAS after mandibular resection in cases where the reconstruction plate could not be placed directly on the mandible before mandibular resection intraoperatively. Among the cases using CAS, we also compared outsourced CAS using TruMatch with in-house CAS. In these comparisons, the 3DD values, which represent the displacement of the mandibular condyle, showed that CAS-based reconstruction methods were significantly more accurate. Furthermore, our in-house CAS was comparable to the outsourced CAS, with almost identical accuracy. There have been previous reports on the application of CAS in mandibular reconstruction. For these methods to be implemented and established as superior techniques, evaluating their accuracy is essential. Measurements used to determine accuracy include ICD, intergonial distance, anterior-posterior distance, and gonial angle (26). However, in many cases of mandibular segmental resection, the mandibular angle and anterior teeth are also resected, and in practice, only the ICD could be measured in almost all our cases. Since the change in ICD may not reflect slight changes before and after surgery, we chose to superimpose the healthy side using pre- and postoperative 3D images and measure the displacement of the affected mandibular condyle as 3DD. Therefore, in our cases, we did not find a significant difference in ICD between non-CAS and CAS, but we did find a significant difference in 3DD.

Several studies have reported on mandibular reconstruction using either outsourced CAS or unique in-house CAS, but few have directly compared the two (14). In our study, no significant

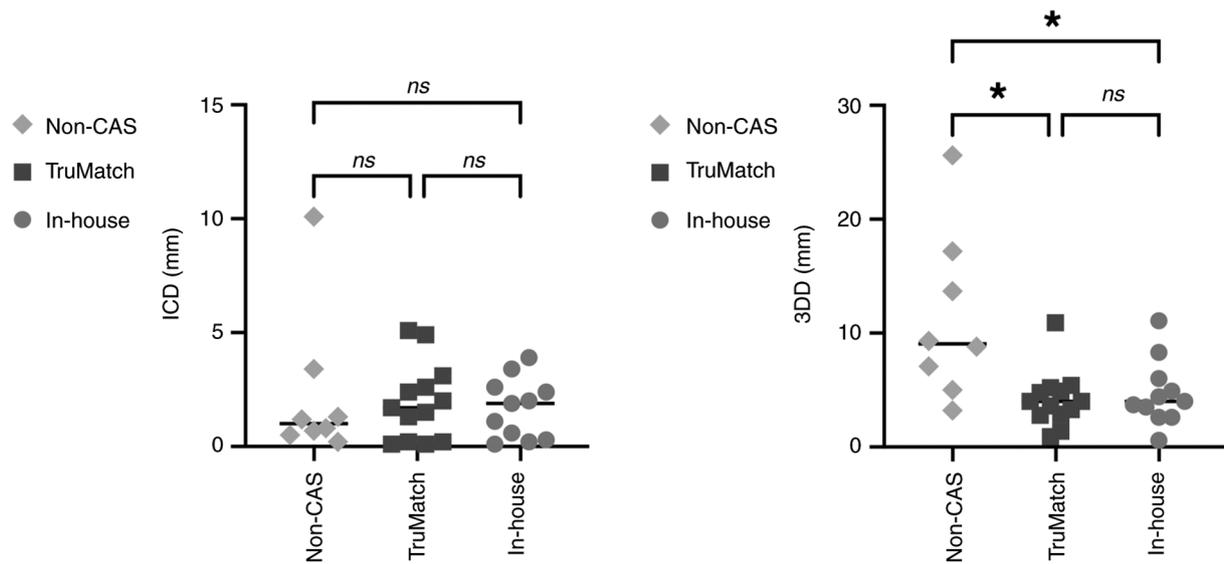


Figure 7. Comparison of 3D accuracy analysis results. The results of comparing ICD and 3DD values for non-CAS, TruMatch, and in-house CAS cases are shown. As shown in the graph on the left, no significant difference is noted in ICD values among the three groups. However, as shown in the graph on the right, the 3DD values were significantly smaller in the TruMatch and in-house CAS groups compared to the non-CAS group. Lines represent the median. *P<0.05. 3DD, 3D deviation distance; CAS, computer-assisted surgery; ICD, intercondylar distance; ns, not significant.

difference in accuracy was observed between in-house CAS and outsourced CAS. Both approaches improved operation time and occlusal relationships, and the fit between the reconstruction plate and the mandible was enhanced. However, TruMatch employs a custom plate, which may contribute to slightly higher accuracy. In-house CAS requires the use of a standard reconstruction plate, which is weaker than the custom-made outsourced plate, and this limitation needs improvement in the future. However, because custom plates take time to manufacture, the TruMatch system requires a minimum of one month for preparation, limiting its usefulness in malignant tumor surgeries. On the other hand, in-house CAS can be used in as little as one week of preparation, making it suitable for emergency surgeries. This explains why our results show a higher proportion of malignant tumor patients in the in-house CAS cases compared to TruMatch cases. Although occlusal stability appeared visually consistent in CAS cases, a more detailed and objective analysis is warranted. Future studies should address this aspect to more accurately quantify functional outcomes. In contrast, occlusal abnormalities were observed in several cases within the non-CAS group, including malalignment and asymmetry of the dental arches, as noted during routine postoperative follow-up and radiographic evaluation. These findings suggest that even minor deviations in mandibular positioning can lead to functional impairment, particularly when preoperative plate fixation is not feasible. While no severe mastication disorders or temporomandibular joint dysfunction were reported within one month postoperatively, the presence of occlusal discrepancies underscores the importance of incorporating functional assessments into future studies. Quantitative evaluation of occlusal force, mandibular mobility, and long-term functional outcomes will be essential to fully understand the clinical impact of CAS-based reconstruction.

Directions for further improving mandibular reconstruction using CAS include improving preoperative surgical planning and revising and upgrading the equipment used

during surgery. For example, when determining the extent of resection, which is a crucial factor in mandibular reconstruction for malignant tumor surgeries, machine learning may be able to automatically determine the appropriate resection extent by superimposing not only CT scans but also magnetic resonance imaging and positron emission tomography-CT images. Furthermore, mathematical modeling and machine learning may reduce the reliance on the capabilities of surgeons and clinical engineers to select the optimal reconstruction solution and suggest the ideal shape of the surgical device (27). Additionally, 3D printed mandibular reconstruction plates are now available and are preferred over pre-bent plates because they offer more accurate results and are less likely to break. However, attention should be given to disadvantages, such as plate exposure, especially if the design becomes too complex (22,28). To minimize the risk of breakage due to bending of ready-to-use reconstruction plates, this can be addressed by developing efficient bending techniques.

Although our in-house CAS system currently relies on commercially available software such as Vincent (Fujifilm, Japan) and 3Shape Dental System (3Shape, Denmark), it is used in a customized manner not originally intended for clinical mandibular reconstruction. To address concerns regarding generalizability and reproducibility, we are actively developing a dedicated software platform that integrates virtual surgical planning, guide design, and plate fitting. This new system aims to standardize the workflow and facilitate broader adoption of in-house CAS techniques in diverse clinical settings.

Prior to implementing the in-house CAS system, we gained experience with several cases using the outsourced TruMatch system. The design of our in-house surgical guides and positioning devices was informed by the structure and functionality of those used in TruMatch, allowing us to adopt and adapt effective design elements. This experience contributed to the reproducibility and reliability of our in-house workflow, despite the continued use of standard reconstruction plates.

In terms of plate fitting accuracy, the TruMatch system clearly outperforms the in-house CAS approach. This limitation arises from manual plate bending, which inevitably introduces gaps between the plate and the bone surface. Such gaps can result in misalignment during fixation, as the plate may be secured in a position deviating from that planned on the 3D model. To mitigate this issue, our in-house CAS workflow incorporates a custom-designed device that enables the precise placement of manually bent plates at the intended location. While this does not eliminate the inherent limitations of manual bending, it ensures that the plate is fixed exactly where planned, thereby improving reproducibility and reducing positional errors.

As a future direction, we aim to develop techniques or tools that further minimize the gap between manually bent plates and the bone surface, enhancing the accuracy and reliability of in-house CAS-based mandibular reconstruction. However, in this study, the fit of the plate was not assessed objectively, as no standardized imaging or intraoperative measurement protocols were implemented. Future studies should incorporate objective methods to evaluate plate fitting accuracy, such as quantitative measurement of the plate-to-bone gap using high-resolution postoperative CT imaging and assessment of the contact surface area with 3D modeling software.

Finally, we acknowledge that this study evaluated surgical accuracy only at approximately 1 month postoperatively. Long-term functional outcomes, including occlusal stability, mouth opening, aesthetic appearance, and postoperative complications such as non-union or infection, were not assessed. These factors are critical for determining the true clinical value of CAS-based mandibular reconstruction. Future prospective studies with extended follow-up periods are warranted to comprehensively evaluate both functional and aesthetic outcomes over time.

In addition to technical improvements, future research should focus on study design enhancements. Given the retrospective nature of the present study, randomization and stratification by surgeon experience were not feasible. Prospective studies with randomized designs and clearly defined surgeon qualifications and experience levels would help reduce potential confounding factors and strengthen the evidence supporting CAS-based mandibular reconstruction.

In conclusion, the use of CAS systems in mandibular reconstruction surgery may be particularly advantageous in cases involving mandibular resection where postoperative occlusal reconstruction is challenging. In-house CAS systems provide comparable and favorable outcomes to outsourced CAS, making them a potentially cost-effective option for precise reconstructive surgery and enabling a greater number of patients to benefit from CAS technology in the future.

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Availability of data and materials

The data generated in the present study may be requested from the corresponding author.

Authors' contributions

ShK, YM, TM and NU conceptualized the study and designed the overall research approach. ShK, RK, KK, ATN and EO performed experiments and ensured their completeness and integrity. ShK and YM confirm the authenticity of the all the raw data. ShK, YM, RK, TM, KK, ATN and EO performed formal statistical analyses. YM and NU acquired funding for the project. ShK, RK, YU, SaK, YMM, AT and KM conducted experimental and clinical investigations. ShK, YM, RK, TM and KK developed and optimized the study methodology, including experimental protocols and analysis pipelines. ShK, YM, RK, TM, KK, AN, EO, YU, SaK, AT, KM and NU provided essential resources, including access to clinical samples, instrumentation and institutional facilities. ShK, YM, RK and TM developed and maintained the software tools used for image processing and data analysis. ShK, YM and NU supervised and validated the study steps and results. ShK produced the visual materials (figures and schematic diagrams) and, together with YM, prepared the initial draft of the manuscript. ShK, SaK, YM, YMM, AT, KM and NU critically revised the manuscript for important intellectual content and approved the final version. All authors read and approved the final manuscript, and agreed to be accountable for all aspects of the work.

Ethics approval and consent for participation

The study was approved by The University of Osaka Graduate School of Dentistry Research Ethics Committee (approval number: R6-E35). All methods were performed in accordance with the relevant guidelines and regulations of the Basel Declaration. Informed consent was obtained from all patients using an opt-out method.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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