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The effect of custom-made surgical guides for the removal of supernumerary impacted teeth

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Abstract

Background Digital technology has been applied in the field of oral surgery. In this study, the efficacy of custom-made surgical guides for the removal of supernumerary impacted teeth in the maxilla was investigated.

Methods The surgical guides were designed with access holes and rods that corresponded to the positions of the impacted teeth and the direction of the approach. The biocompatibility of the 3D-printed materials was first assessed in vitro. The efficacy of the printed surgical guides was evaluated in an in vitro experimental model study performed by 32 oral surgeons on 3D-printed maxillary models to evaluate various surgical parameters and complications, and a clinical observation study of 30 patients.

Results The 3D-printed materials demonstrated excellent biocompatibility when they were fabricated according to the manufacturer's protocol. In the in vitro study, the guides did not significantly reduce the extraction time or bone removal volume compared with those of the control group. However, they effectively prevented mispositioning of bone removal sites and reduced the incidence of root damage. Clinically, all surgical guides resulted in safe and precise bone removal without major complications.

Conclusions The benefit of the surgical guide system used in the present study showed limited, but it might minimize complications and enhance the safety during supernumerary impacted tooth removal.

Keywords Surgical guide, supernumerary impacted teeth, digital dentistry, experimental study

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Background

Supernumerary impacted teeth are commonly found in the maxillary midline area and often require extraction because of their potential to cause a number of orthodontic discrepancies, including delayed eruption or retention of adjacent teeth with crowding, spacing, and abnormal root formation [1, 2]. However, the extraction procedure must be performed with maximum caution because of the risk of complications, such as damage to the adjacent tooth roots or destabilization of neighboring teeth due to the bone removal procedure [3]. Although supernumerary tooth extraction is a fundamental procedure for oral surgeons, it requires careful technique because of the risk of complications such as root or nerve damage.

In recent years, digital technologies have been increasingly integrated into oral surgery, including surgical simulation platforms, CAD/CAM systems, and navigation-guided procedures [4–7]. Three-dimensional (3D) digital technology has also been applied to the extraction of impacted teeth, with several studies reporting successful outcomes using surgical guides to assist in the removal of supernumerary impacted teeth [8–11]. These technologies enable precise determination of the 3D position and angulation of the impacted tooth, as well as the optimal surgical approach. However, many previously reported guides functioned primarily as locators, indicating the position of the tooth but not providing directional or depth guidance for bone removal [8–11].

To reduce the risks of complications during the extraction of supernumerary teeth, we developed a digital workflow to create custom surgical guides that accurately indicate the necessary extent of bone removal. In our routine practice, we produce in-house, custom-made guides with a drilling hole and an indicating rod to direct the angle and extent of bone removal in more challenging cases. Nonetheless, the effectiveness of this guide type has not been objectively established, and few studies have rigorously evaluated surgical guides for supernumerary maxillary tooth extraction. Furthermore, despite manufacturer assurances of biocompatibility, the cytocompatibility of guide materials under clinically realistic postprocessing conditions has not been fully characterized.

Therefore, this study aimed to evaluate the usefulness of custom surgical guides for extracting supernumerary impacted maxillary teeth. First, in vitro surgical guide material characteristics and cell behaviors on the materials were investigated using murine osteoblastic MC3T3E-1 cells. We subsequently conducted a model-based experiment using an in-house 3D-printed maxillary model with fully impacted supernumerary teeth and a corresponding surgical guide. In this experiment, 32 oral surgeons performed extractions with and without the guide, enabling comparisons of the efficiency and invasiveness between guided and unguided procedures. Additionally, we performed the clinical cases of 30 patients who underwent guided extraction.

Methods

Materials

A 3D printer (Form3B®, Formlabs, Somerville, MA, USA) and two types of 3D-prining resin materials, namely, biocompatible resin (Surgical Guide Resin®, Formlabs) and opaque model resin (Model Resin V3®, Formlabs), were utilized in the present study. The compositions of both resin materials include methacrylate monomer, urethane dimethacrylate and photoinitiator. Surgical Guide Resin® is approved as a class I biocompatible resin (EN-ISO 10993-1:2009/AC:2010, USP Class VI) suitable for surgical and pilot drill guides. Model Resin V3® is usually used to print dental restorative models.

Preparation of custom-made surgical guides

The workflow for the preparation of surgical guides is illustrated in Fig. 1. Anonymized DICOM data from patient computed tomography (CT) scans were utilized, and the maxillary dentition, maxillary bone structure, and impacted teeth were segmented at the bone level using 3D visualization and analysis software (Amira 3D® software; Thermo Fisher Scientific, Waltham, MA, USA). If the artifacts of metal restorations disturbed the segmentation of the dental crown structures, standard triangle language (STL) data of the dental model were further acquired, and the 3D occlusal surface data of the dental arch and accurate bone volume data were merged. The segmented 3D structures were extracted to confirm the location of the supernumerary teeth and simulate realistic extraction approaches, considering the impact on permanent tooth roots (Fig. 1B). The surgical guide was designed to support the teeth and bone, and the designed guide had a thickness of approximately 2 mm. Access holes corresponding to the size of the supernumerary teeth were created by hollowing out the tooth morphology along the predetermined extraction direction; however, the depth was not specified. The details of design and fabrication procedures for surgical guides used for the removal of impacted teeth have been previously reported [12].

The surface data of the designed surgical guides were exported as STL data and printed using a 3D printer (Fig. 1C). Each cured material was postprocessed and disinfected prior to intraoperative use. For the in vitro extraction model study, the components of the impacted tooth and three maxillary model parts were exported as STL files and fabricated. For the surgical guide and impacted tooth parts, a transparent, biocompatible resin was used. For the maxillary model parts, opaque model resin was selected.

In vitro material characteristics

A disk with a diameter of 13.5 mm and a thickness of 2 mm was designed using CAD software (Fusion360®, Autodesk, San Francisco, CA, USA). After printing, in accordance with the manufacturer's recommendation, the disks were washed with 95% isopropyl alcohol (IPA) for 20 min and postcured using a UV curing machine at 70 °C for 30 min. Prior to experimentation, all the discs were disinfected using a chlorhexidine-based disinfectant solution (Maskin R ethanol solution; NIPRO; Osaka, Japan) or autoclaved at 121 °C for 15 min. In

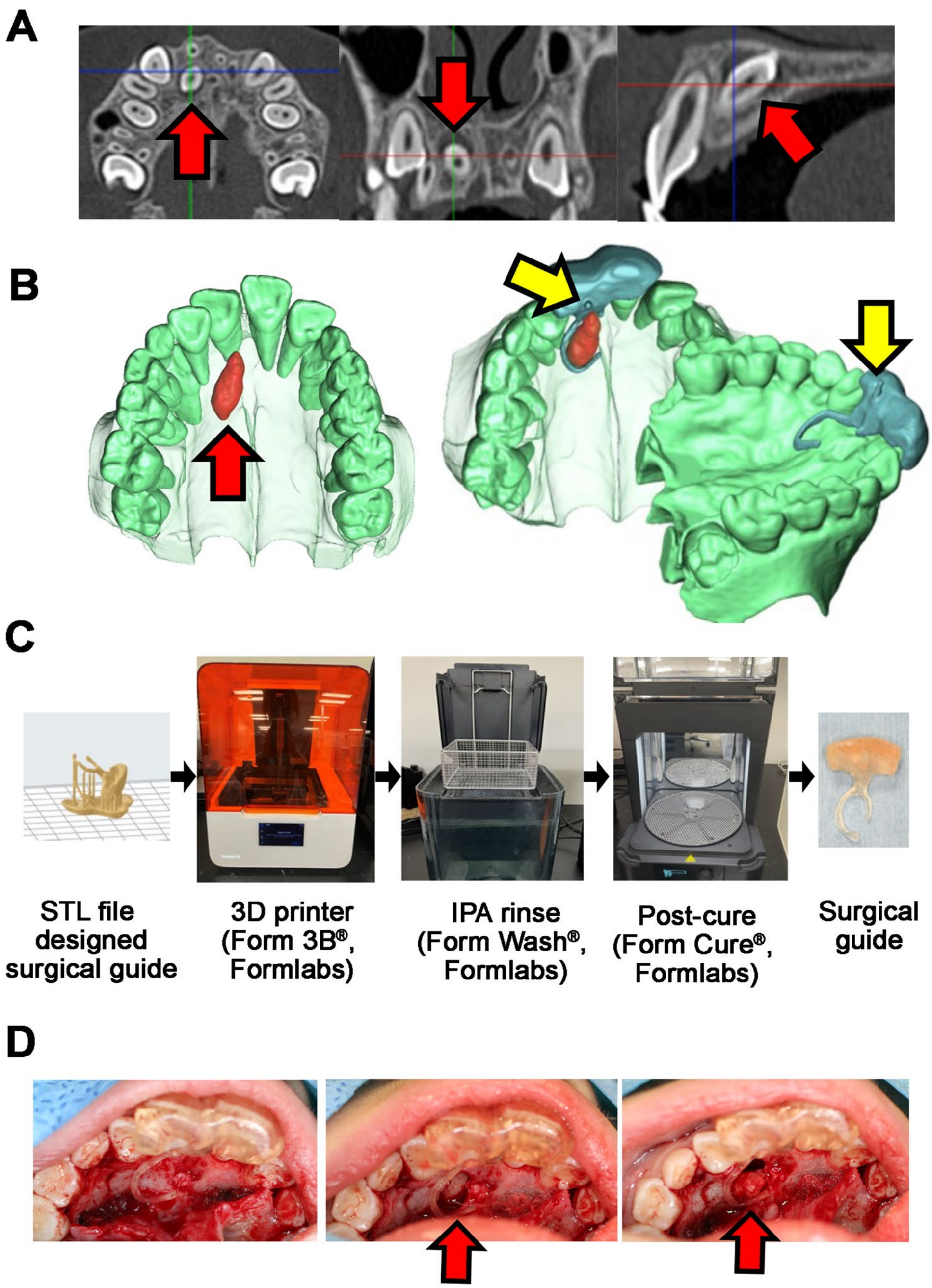

Fig. 1 Workflow of the surgical guide design, preparation and application. **A** CT images showing a supernumerary impacted tooth in the maxilla (red arrows). **B** Segmented 3D data of the teeth and maxilla. The red arrow shows the supernumerary impacted tooth for extraction. The segmented 3D data were simulated for realistic extraction approaches, considering the impact on permanent tooth roots. The surgical guide designed for extraction includes an indication rod (yellow arrows), which shows the direction of the bone drilling approach. **C** The surface data of the designed surgical guides were exported as standard triangle language (STL) data and printed by a 3D printer. Each cured material was postprocessed, including isopropyl alcohol (IPA) rinsing, postcuring and disinfection before use. **D** Intraoperative photographs. Red arrows indicate the supernumerary impacted teeth

vitro materials experiments compared the following 4 test groups (Fig. 2A): (1) insufficient IPA rinsing for 5 s followed by the recommended procedure (iR) group, (2) insufficient postcure treatment for 1 min after sufficient IPA rinsing (iP) group, (3) chlorhexidine disinfection for 3 min after the recommended posttreatment (CHX) group, and (4) autoclave sterilization after the recommended posttreatment (AC) group.

Vickers hardness tests were performed using a calibrated microhardness tester (HM-102; Mitutoyo Co., Kanagawa, Japan). The wettability of the sample surfaces was evaluated by measuring the static contact angle using

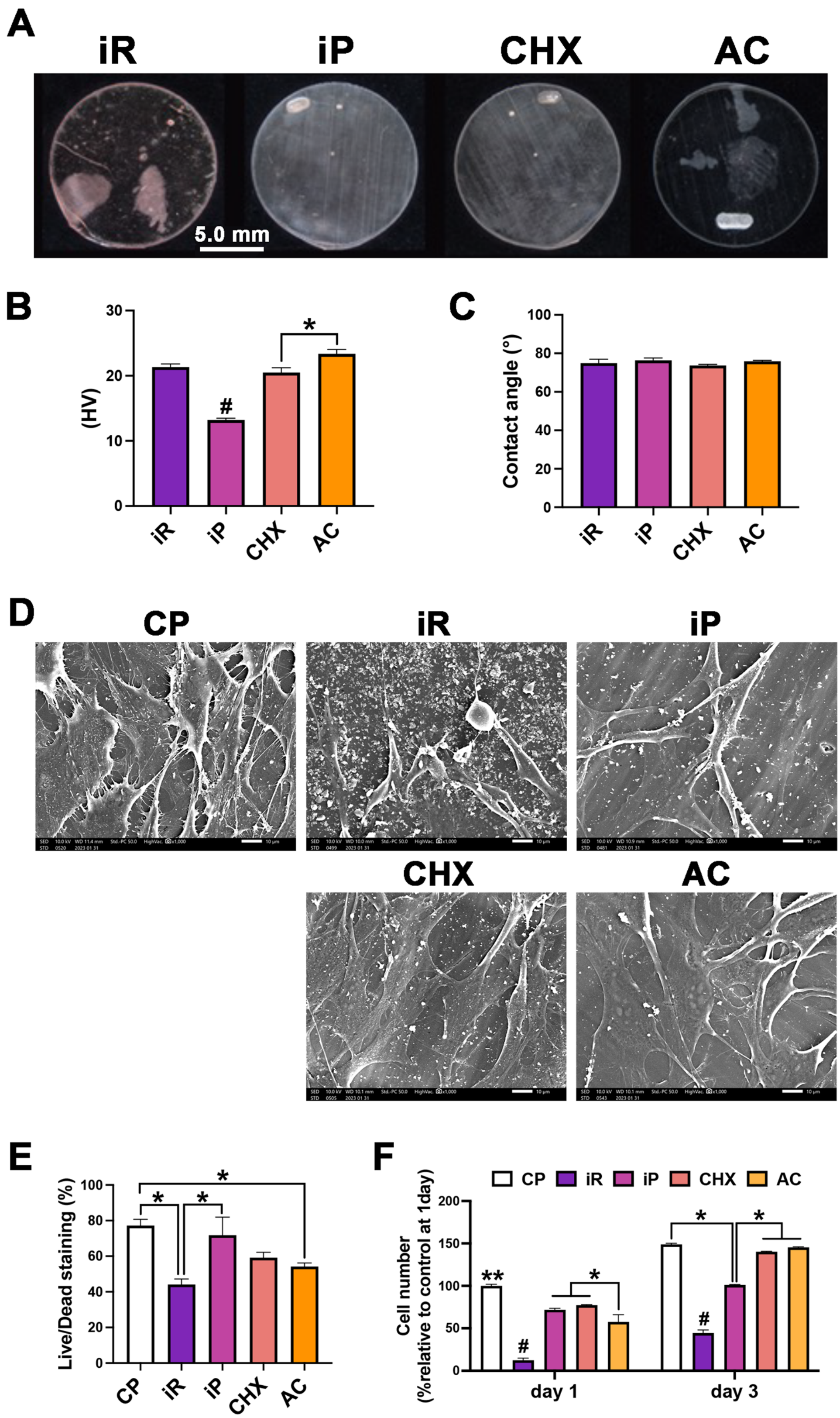

Fig. 2 (See legend on next page.)

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Fig. 2 In vitro material properties and cell assays. **A** The test materials. Discs 13.5 mm in diameter × 2 mm in height of surgical guide resin materials were treated with (1) insufficient IPA rinsing for 5 s followed by the recommended procedure (iR group) or (2) insufficient postcure treatment for 1 min after sufficient IPA rinsing (iP group), (3) chlorhexidine disinfection for 3 min after the recommended posttreatment (CHX group), or (4) autoclave sterilization after the recommended posttreatment (AC group). **B** Vickers hardness of each tested material. **C** Contact angles of the surfaces of materials. **D** SEM images of MC3T3E-1 cells cultured on discs from the (1) control culture plastic (CP) group, (2) iR group, (3) iP group, (4) CHX group, and (5) AC group. Scale bars indicate 10 μm. (E) Live/dead cell assay at 24 h after the cells were seeded on each group of materials. **F** Cell proliferation in the tested groups at 1 and 3 days post-seeding (# denotes significantly lower than all other modalities, $p < 0.05$; * denotes a statistically significant difference between groups, $p < 0.05$; and ** denotes values significantly higher than those of all other treatment modalities, $p < 0.05$)

the sessile drop method on an optical contact angle goniometer (LSE-ME3, NiCK, Saitama, Japan).

Cell culture

Mouse osteoblast-like MC3T3-E1 cells (RIKEN, Saitama, Japan) were utilized. The cells were maintained in α-MEM (Gibco, Life Technologies, Carlsbad, CA, USA) supplemented with 10% fetal bovine serum (FBS; Gibco) supplemented with 1% antibiotics (Gibco) at 37 °C with 5% CO_2. Cells were passaged at 70–80% confluence using 0.05% trypsin/EDTA and seeded on four types of disks—1) control plastic (CP; Celldesk LF, Sumitomo Bakelite, Tokyo, Japan), 2) iR, 3) iP, 4) CHX, and 5) AC, in 24-well plates at 1.0×10^4 cells per well.

Scanning Electron Microscope (SEM) Imaging

Cells cultured on each disk for 24 h were fixed overnight at 4 °C in 2.5% glutaraldehyde solution, dehydrated in an elevated series of ethanol solutions and dried with hexamethyldisilazane (Sigma Aldrich, St. Louis, MO, USA). The dried samples were attached to aluminum stubs (Nisshin-EM, Tokyo, Japan) and sputter-coated with platinum using a sputtering device (E-1030 Ion Sputter, HITACHI, Tokyo, Japan). SEM images were acquired using a scanning electron microscope (JSM-IT200; JEOL, Tokyo, Japan).

Live/dead cell assay

Twenty-four hours after cell seeding, the cells were evaluated using a live/dead staining assay according to the manufacturer's protocol (Live-Dead Cell Staining Kit, Enzo Life Sciences, Farmingdale, NY, USA). The fluorescence was quantified with an inverted fluorescence microscope (Olympus FSX-100; Olympus, Tokyo, Japan). The cell quantities are expressed as the percentage of live-to-dead cells.

Cell proliferation assay

Cell proliferation was investigated using an MTS colorimetric assay (Promega, Madison, WI, USA). At 1 and 3 days after cell seeding, the number of living cells was quantified with a microplate reader (SH-900, CORONA ELECTRIC, Ibaraki, Japan).

In vitro model experiments

This in vitro model study was approved by the Ethics Committee of Nippon Dental University (Approval No. NDU-T2021-29). Preoperative CT data from two patients previously treated for supernumerary impacted teeth in the anterior maxilla were anonymously used to construct maxillary dental models containing fully impacted supernumerary teeth for research purposes. The selected cases included one mixed-dentition case (Case 1) and one permanent dentition case (Case 2), both amenable to a palatal approach and requiring a comparable extent of bone removal for extraction (Fig. 3).

Model-based experiments were conducted between November and December 2021. Participants were dentists engaged in oral surgery practices at the Department of Oral Surgery, Nippon Dental University Hospital. Each participant performed extraction procedures on two models—Case 1 and Case 2. For one of the models, a surgical guide was used. Participants were randomly assigned to one of four experimental patterns:1) Case 1 with a surgical guide → Case 2 without a surgical guide, 2) Case 1 without a surgical guide → Case 2 with a surgical guide, 3) Case 2 without a surgical guide → Case 1 with a surgical guide, 4) Case 2 with a surgical guide → Case 1 without a surgical guide. Prior to the experiment, each participant was provided with an explanation of the study purpose using a test model (not corresponding to Case 1 or 2). In addition, an instructional video was shown to demonstrate how to use the model and surgical guide, as well as how to perform the experimental procedures. The extraction procedures were performed without the use of a phantom on a laboratory workbench.

The incision line length (mm) and flap area (mm^2) were measured from standardized photographs (fixed distance and angle) using image analysis software (Photoshop CC; Adobe, San Jose, CA, USA). The extraction time was recorded from the start of bone removal to the completion of tooth extraction with elevators or root tip picks; procedures exceeding 15 min were discontinued. The parameter, mispositioning was defined as either a side error (left/right confusion) or a positional deviation of more than one tooth. Furthermore, after extraction, the models were scanned using micro-CT (ScanXmate-D100SS270; Comscantecno, Kanagawa, Japan), and the bone removal volume (mm^3) was measured using Amira®

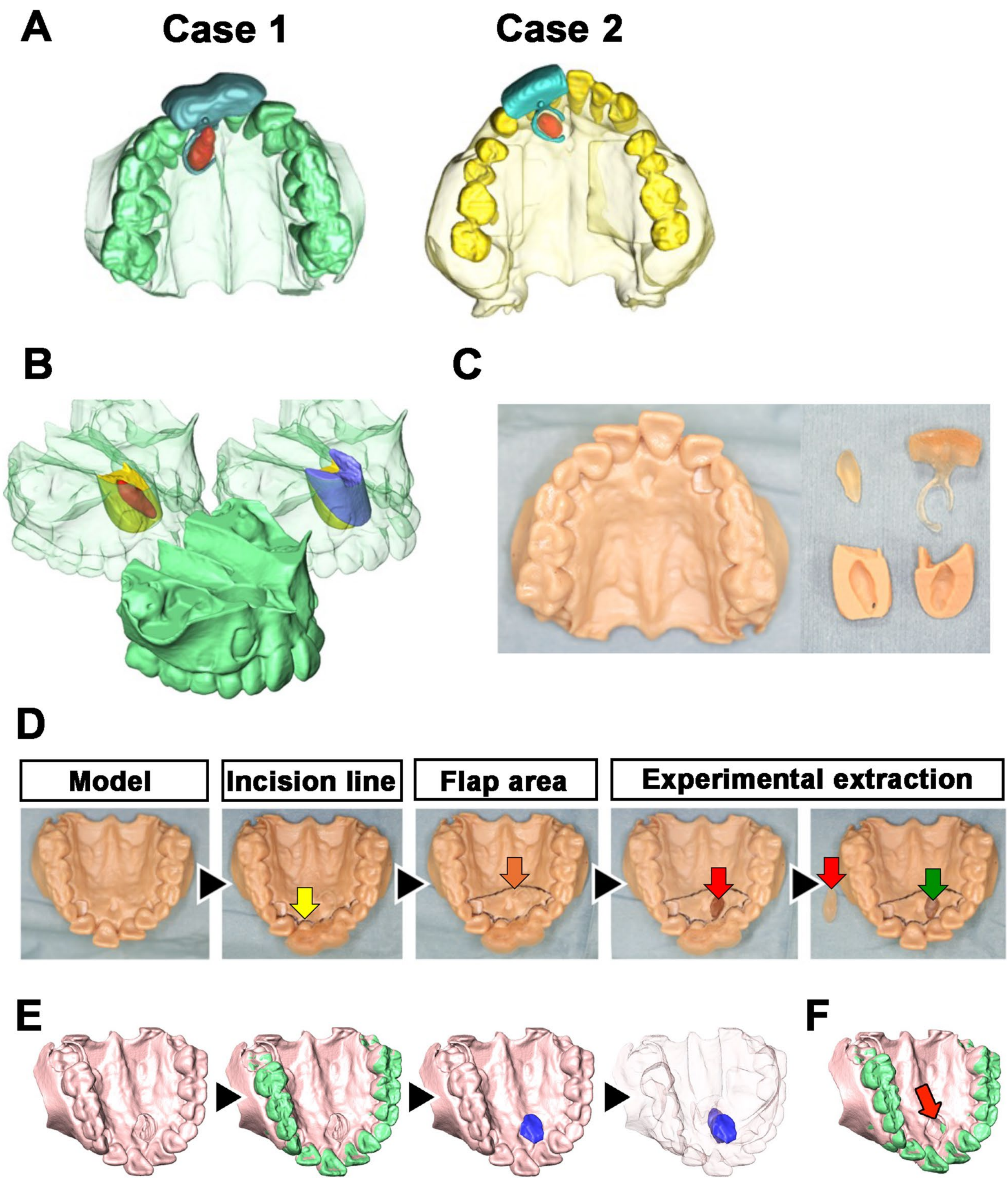

Fig. 3 Two cases used for the in vitro model experimental study. **A** Overview of the two cases of 3D-segmented models from CT data and designed surgical guides (light blue). **B** Model parts for 3D printing. Red represents the supernumerary tooth, and yellow, blue and green represent the maxillary bone parts. **C** The printed parts for the experiment. Model Resin® (light brown) was used for maxillary bone parts, and Surgical Guide Resin® (clear) was used for the supernumerary impacted tooth and surgical guide. **D** The evaluation process. The participants drew the incision line (yellow arrow) and flap area (orange arrow) after CT was read on the PC, and the impacted tooth was experimentally extracted (red arrow). The green color indicates the bone defect after extraction. **E** Micro-CT analysis after extraction. The micro-CT data of the extracted maxillary model were visualized and merged with the initial CT data. The removed bone (blue) volume was calculated. **F** Root damage analysis. Root damage was confirmed when merged images demonstrated exposure of adjacent tooth roots

software. If bone removal extended to adjacent permanent tooth roots, it was classified as root damage.

Clinical evaluation of surgical guide efficacy in patients

The study was conducted between August 2021 and February 2024. Patients with supernumerary impacted teeth who required preoperative CT imaging and for whom the use of a surgical guide was considered beneficial were included in this clinical observation study. Patients were excluded if adjacent teeth were missing, if the surgeon determined the use of a surgical guide would not be beneficial. As an exploratory study, the sample size was not determined by statistical inference or power calculations. This clinical observational study was approved by the Ethics Committee of Nippon Dental University (Approval No. NDU-T2021-19). Custom-made surgical guides were prepared as described above, and the incision line was selected according to the access hole position so that the gingival periosteal flaps were elevated with ideal and minimal exposure of the bone. The bone over the impacted teeth was removed using a round bur along the preoperatively determined access hole, revealing the impacted supernumerary teeth. After sufficient bone removal, the supernumerary teeth were extracted using an elevator. The wound was then thoroughly rinsed and closed primarily with resorbable sutures (Fig. 1D). Patient age, sex, number of extracted teeth per patient, angulation of impacted teeth, anesthetic modality, surgical approach, operative time, and intraoperative and postoperative complications were observed and summarized from clinical records. The operation time (extraction time) was defined as the total surgical time from the initiation of the incision to the completion of suturing. The surgery was performed by the one of the authors, board-certified oral and maxillofacial surgeons accredited by the Japanese Society of Oral and Maxillofacial Surgeons.

Statistical analysis

For in vitro material and cell experiments, at least three independent specimens were assessed. The mean and standard error are presented, and the data were analyzed for statistical significance using one-way ANOVA with the Tukey test for material mechanical tests and live/dead assays and two-way ANOVA with the Tukey test. For the in vitro model study, graphs were plotted with individual data points, and the medians are indicated by horizontal lines. Differences in extraction time based on procedure order were analyzed using the Wilcoxon signed-rank test. The number of additional bone removals and root damage events with or without surgical guidance were analyzed using Fisher's exact test. Other comparisons were performed using the Mann–Whitney U test. A p value of <0.05 was consistently considered to indicate statistical significance (GraphPad Prism 10, GraphPad Software, San Diego, CA, USA).

Results

Biocompatibility of the surgical guides

The material properties, cell viability, and proliferation were evaluated in an in vitro study (Fig. 2). In accordance with the manufacturer's recommendations, appropriate isopropyl alcohol (IPA) rinsing, post-curing, and disinfection (either chlorhexidine [CHX] or autoclaving [AC]) are required to ensure biocompatibility. The biocompatible resin was generally clear after proper treatment. However, insufficient IPA rinsing resulted in a sticky and dusty surface (Fig. 2A). In addition, inadequate post-curing or CHX disinfection produced a relatively white-colored surface (Fig. 2A).

Vickers hardness testing revealed that the iP group exhibited the lowest hardness, whereas the AC group was harder compared with the CHX group (Fig. 2B). Wettability testing revealed no significant differences among the groups (Fig. 2C). SEM revealed that the CHX- and AC-treated groups presented cell morphologies comparable to those of the control plastic group (CP), whereas the iR and iP groups presented fewer spread cells on their surfaces (Fig. 2D). Similarly, live/dead assays revealed lower viability in the iR group than in the CP and iP groups, and proliferation assays revealed significantly fewer cells in the iR group than in all the other groups on both days 1 and 3 (Fig. 2E, F). Furthermore, on day 3, the CHX- and AC-treated groups exhibited greater viability compared with the CP group (Fig. 2F).

Efficacy of surgical guide evaluated using the in vitro model experiment

Among the 32 participants, 20 were male (62.5%), and 12 were female (37.5%). Clinical experience in oral surgery ranged from 0.6 to 35 years (mean, 9.5 years; median, 4.5 years). Case 1 involved a mixed dentition stage, whereas Case 2 involved a permanent dentition stage. Both patients had a fully impacted supernumerary tooth in the right maxillary central incisor region. First, in the group that underwent extractions without surgical guides, the CT review time, extraction time, and bone removal volume were evaluated to compare the difficulty of the extraction between Cases 1 and 2 (Fig. 4). No statistically significant differences were observed in CT reading time or bone removal volume between the two cases. However, the extraction time was significantly longer in Case 1 than in Case 2, indicating that Case 1 required more technically difficult extraction (Fig. 4B). To compare the effect of extraction order, the first and second extractions were performed by the same participant (Fig. 4D). Although the second extraction tended to be faster, the difference did not reach statistical significance (Fig. 4D).

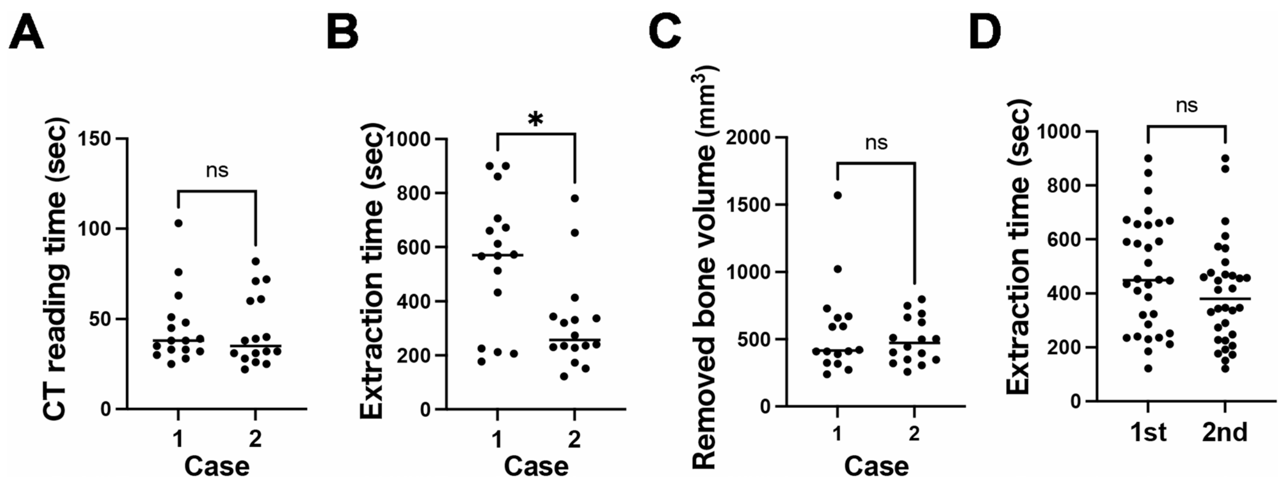

Fig. 4 Extraction difficulty between cases without surgical guides. **A** CT reading time between Case 1 and Case 2. **B** Extraction time between Case 1 and Case 2 without surgical guides. **C** Bone removal volume between Patient 1 and Patient 2. **D** Comparison of extraction times between the first and second extractions in the same case. Note: ns indicates no statistically significant difference between groups; * indicates a statistically significant difference between groups ($p < 0.05$)

Furthermore, the effect of the surgical guide in Case 1 was investigated (Fig. 5). Among the 16 participants who did not use a surgical guide, two were unable to complete the extraction within the designated 15-minute time limit. In contrast, all participants underwent successful extraction with a surgical guide. The guide supported the avoidance of bone removal on the opposite side (misposition) and reduced the risk of root injury (Fig. 5E, F). The incision lines tended to be longer and the flap areas larger, whereas the extraction time tended to be shorter (Fig. 5B-D). Nevertheless, no statistically significant differences were detected between groups in terms of CT reading time, incision line length, flap elevation area, extraction time, number of mispositioned bone removals, number of adjacent root injuries, or bone removal volume (Fig. 5). Only a comparison of the total number of damaged roots revealed the positive efficacy of surgical guide use.

In Case 2, the surgical guide similarly aided in avoiding unnecessary bone removal and minimizing the risk of root damage (Fig. 6). Unlike that in Case 1, the extraction time tended to be slightly longer in the surgical guide group (Fig. 6D). Like in Case 1, no statistically significant differences in CT reading time, incision line length, flap elevation area, extraction time, subject number of mispositioned bone removals, subject number of adjacent root injuries, damaged root number, or bone removal volume were noted between groups (Fig. 6).

Efficacy of surgical guides in clinical cases

A total of 30 patients (14 males, 16 females; mean age, 19.0 years; range, 7–40 years) underwent extraction of supernumerary impacted teeth using a custom-made surgical guide (Table 1). In total, 41 impacted teeth were removed, with a mean of 1.37 teeth per patient (range, 1–6). The directions of impaction included 13 proclined, 19 inverted, and 9 horizontal. General anesthesia was administered in 16 patients, and local anesthesia was administered in 14 patients. A palatal approach was used for 26 teeth, whereas a labial approach was used for 5 teeth. The mean extraction time was 31.6 min per tooth (range, 8–70 min).

No patient experienced postoperative bleeding or other major complaints. Postoperative panoramic radiographs revealed no evident damage to the roots of adjacent permanent teeth. Minor complications included partial necrosis of the gingiva in 2 patients, infection in 1 patient, and temporary mobility of an adjacent tooth in 1 patient.

Discussion

The potential advantages of using surgical guides in the extraction of fully impacted teeth include providing a reference for incision planning, preventing extraction of the wrong tooth, reducing the risk of damage to adjacent permanent roots, shortening the extraction time, and minimizing the extent of bone removal [13]. In the present study, the efficacy of a surgical guide for maxillary supernumerary impacted teeth was investigated from multiple perspectives, including material testing, cell culture experiments, in vitro model studies, and clinical application.

Manufacturers guarantee the safety and performance of 3D-printed materials only when they are fabricated according to their recommended protocols. However, for in-house 3D printing systems and clinical use, users must carefully consider post-processing protocols to ensure safety. In fact, most of the specimens printed on

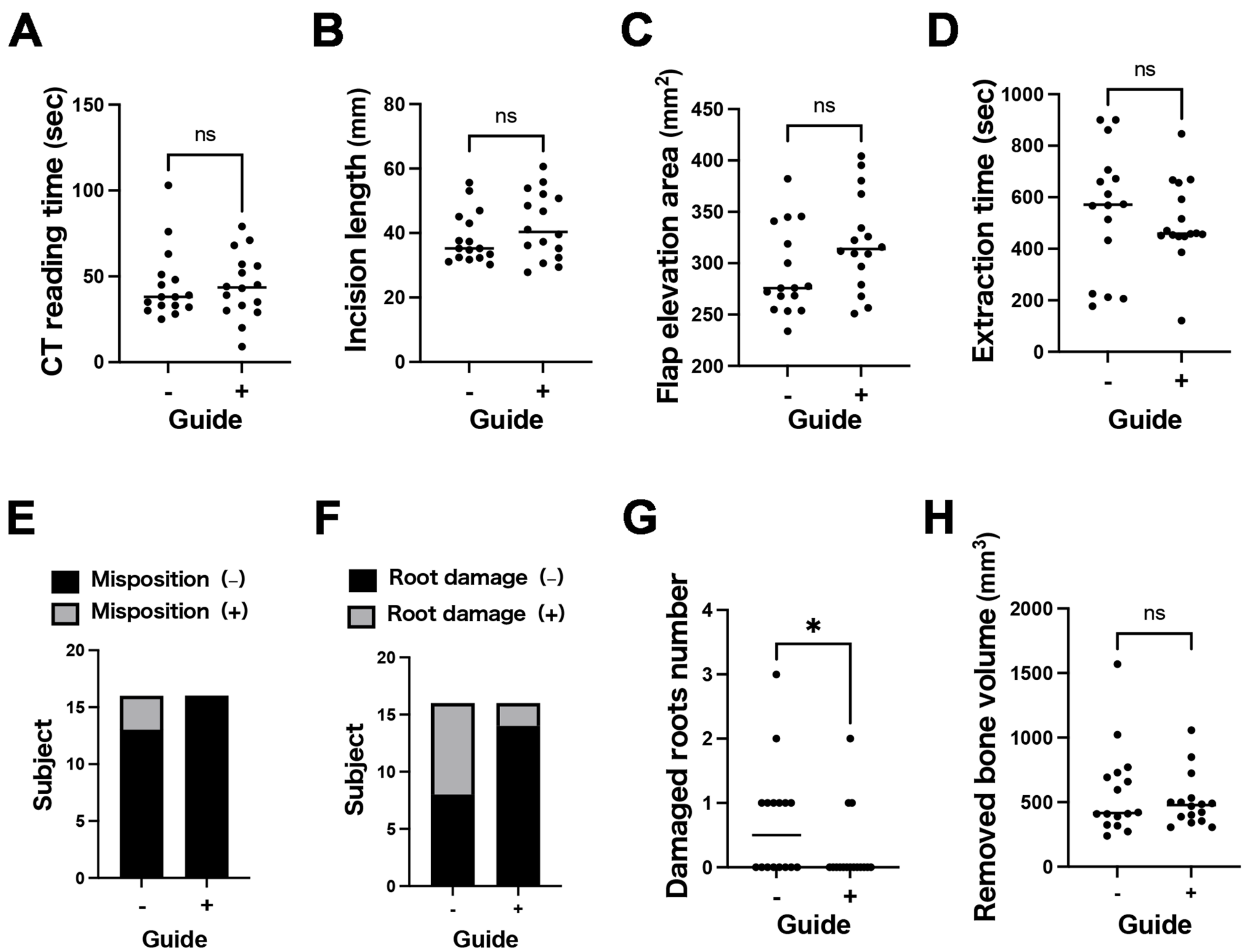

Fig. 5 Effect of the surgical guide in Case 1. **A** CT reading time between the two groups with and without the use of a surgical guide. **B** Length of the incision between the two groups with and without the use of a surgical guide. **C** Drawn flap elevation area between the two groups with and without the use of a surgical guide. **D** Extraction time between the two groups with and without the use of a surgical guide. **E** The number of participants who underwent misposition of bone removal between the two groups with and without the use of a surgical guide. **F** Comparison of the number of participants with root damage between the two groups with and without the use of a surgical guide. **G** Number of damaged roots between the two groups with and without the use of a surgical guide. **H** Bone removal volume between the two groups with and without the use of a surgical guide. Note: ns indicates no statistically significant difference between groups; * indicates a statistically significant difference between groups ($p < 0.05$)

3D printers require postprocessing after the printing is finished, including the removal of support material, final polymer curing, and any finishing techniques such as sanding, polishing, and sealing [14]. Therefore, this study examined the influence of each post-treatment step on the mechanical properties and cytotoxicity of 3D-printed surgical guides. The photopolymerization printer used in this study required immersion of the printed part in an isopropyl alcohol (IPA) bath for a specified period, followed by post-curing with ultraviolet light and heat (Fig. 1C).

Vickers hardness testing revealed that the insufficient post-cure group exhibited the lowest hardness, whereas autoclave sterilization (AC group) increased the hardness compared with chlorhexidine disinfection (CHX group) (Fig. 2B). These results suggest that heating increases material hardness. However, overcuring may cause brittleness and increase the risk of partial fracture, while undercuring may leave residual toxic resin, posing safety concerns if in contact with patients, and may also compromise mechanical strength [14, 15]. Uncured (meth) acrylate resins are known to exhibit high irritancy or even cytotoxicity [16]. Cell viability assays revealed lower viability in the insufficient IPA rinsing (iR) group than in the control and insufficient postcure treatment (iP) groups (Fig. 2E, F). These findings indicate that IPA rinsing is a particularly critical step for ensuring biocompatibility, potentially more so than the photopolymerization step itself. The user should be aware of the criticality of this step and the potential risks. Török et al. reported that both plasma sterilization and steam sterilization at 121 °C were suitable for sterilizing tested 3D-printed surgical

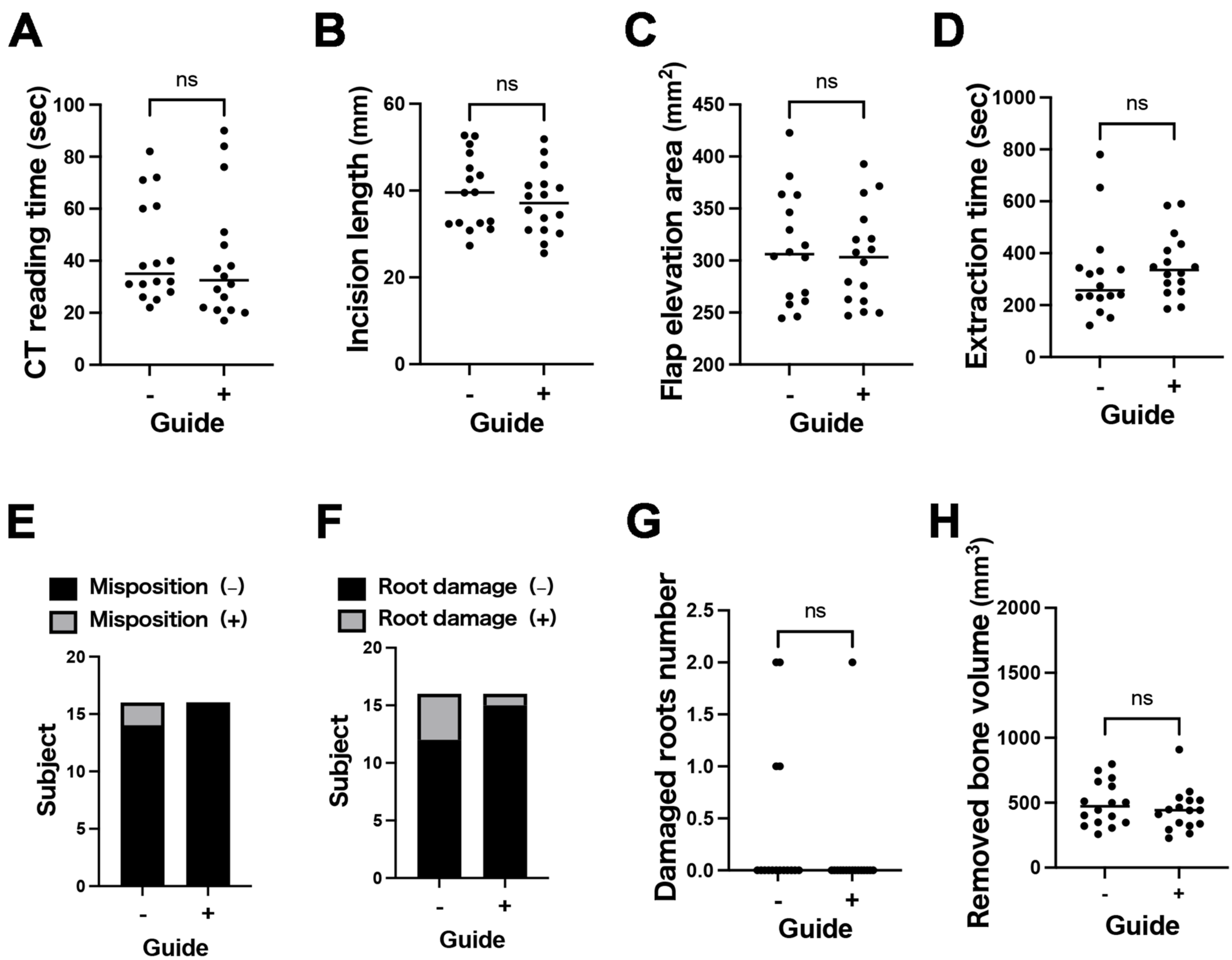

Fig. 6 Effect of the surgical guide in Patient 2. **A** CT reading time between the two groups with and without the use of a surgical guide. **B** Length of the incision between the two groups with and without the use of a surgical guide. **C** Drawn flap elevation area between the two groups with and without the use of a surgical guide. **D** Extraction time between the two groups with and without the use of a surgical guide. **E** The number of participants who underwent misposition of bone removal between the two groups with and without the use of a surgical guide. **F** Comparison of the number of participants with root damage between the two groups with and without the use of a surgical guide. **G** Number of damaged roots between the two groups with and without the use of a surgical guide. **H** Bone removal volume between the two groups with and without the use of a surgical guide. Note: ns indicates no statistically significant difference between groups

Table 1

Patients (*N*)	30
Age (year)	Average 19.0 (range; 7–40)
Sex (N)	Male 14, Female 16
Extracted tooth number (N)	Total 41, Average 1.37 (range; 1–6)/patient
Direction of impacted teeth (N)	Proclined 13, Inverted 19, Horizontal 9
Anesthesia (N)	GA 16, LA 14
Approach procedure (N)	Palatal 26, Labial 5
Extraction time (min/tooth)	Average 31.6 (range; 8–70)
Complications (N)	Partial necrosis of gingiva 2, Infection 1, Temporal mobility of adjacent tooth 1

GA; general anesthesia, *LA*; local anesthesia

guides [17]. Similarly, the IPA and AC groups in the present study resulted in both suitable for biocompatibility.

In the in vitro model experiment, the surgical guide did not significantly reduce the extraction time or bone removal volume in either case. This may be attributed to the limited sample size and the fact that all participants were trained oral surgeons capable of performing extractions without a guide. In Case 1, six participants required more extensive bone removal than initially planned, suggesting insufficient flap design. In clinical settings, this would likely lead to additional incisions and longer surgery times. Thus, surgical guides may also be advantageous for planning appropriate incision and flap designs. In Case 2, where extraction was relatively easier, the time required to attach and remove the unfamiliar guide may have contributed to a slight increase in extraction time.

All participating surgeons for in vitro model study were trained in Department of Oral and Maxillofacial Surgery. No significant differences were observed in extraction time and bone removal volume in each setting, when compared between with ≤ 3 years and > 3 years of experience (Supplemental Fig. 1). Nevertheless, two participants with less than three years of oral surgery experience were unable to complete the extraction within the 15-minute limit without a surgical guide in case 1, suggesting that the guide is particularly beneficial for less experienced surgeons. Furthermore, in both tested cases, some participants—regardless of experience—mistakenly removed bone from the opposite side when they did not use the guide. The potential benefit of surgical guides lies in enhancing safety by securing tooth positions and thereby helping to avoid adverse medical events.

The previous study by Lee et al. [18] have reported significant reductions in extraction time and bone window area when using surgical guides in similar simulation models. However, in their study, all participants were residents, and each participant used the same model twice—first without a guide and subsequently with a guide after a two-week interval. This sequential design may have introduced bias related to prior familiarity with the model and procedural learning effects. The different experimental design may partly explain why statistically significant differences in parameters such as extraction time or bone removal volume were not observed in the present study.

A limitation of the model experiment was the model lacked the elasticity of natural alveolar bone, which necessitated slightly greater bone removal than would typically be required in clinical practice. However, the tactile sensation during bone removal with a round bur closely resembled that of natural bone, whereas the tooth model, fabricated from a harder and more transparent resin material, provided a distinct tactile contrast and different visualization. The ability of the model to accommodate both bone cutting and tooth extraction makes it a valuable training tool for early-career oral and maxillofacial surgeons as well as dental students.

Furthermore, some participants were unfamiliar with proper surgical guide positioning or uncertain about the correct approach to bone reduction. To assess whether unfamiliarity influenced performance, the extraction times for the first and second procedures were compared (Fig. 4). Although the second extraction tended to be faster, the difference was not statistically significant. Therefore, we analyzed the effect of surgical guide use without distinguishing between first and second extractions. Although, we adopted a fully randomized design using two different models and recruited 32 experienced oral surgeons in the present study, only two models were used in the in vitro model experimental study. The use of alternative model types represents an important direction for future research.

Previous clinical reports on 3D-printed surgical guides for impacted supernumerary tooth extraction are limited, with most describing guides that indicate only partial tooth location for median supernumerary teeth in case reports [8–11]. Notably, Liu et al. conducted a randomized controlled trial in 40 patients and evaluated the efficiency and safety of a surgical guide for deeply impacted supernumerary teeth in the anterior maxilla [19]. Their findings demonstrated that surgical guides significantly reduced the operative time and postoperative complications and improved surgical quality, patient satisfaction, and procedural ease, although certain limitations of the technique remain [19].

In the present study, 30 patients with a total of 41 impacted supernumerary teeth underwent extraction using the custom-made surgical guides we developed. In all the cases, the guides facilitated smooth removal of the impacted teeth. Only minor postoperative complications were observed (Table 1); however, all complications resolved completely within a few months.

The primary limitation of this clinical observational study was its design. The study was neither controlled nor randomized, preventing direct comparison of surgical guide use with conventional extraction techniques. Nevertheless, the clinical observational study was intended to demonstrate that a surgical guide could be feasibly applied in real-world clinical settings, without adverse events and without reducing surgeon stress during routine procedures. Furthermore, the study was conducted at a single institution, the generalizability of the findings to other clinical settings may be limited.

In addition, alternative guidance modalities, such as dynamic navigation systems, augmented reality, and robotic-assisted surgery, are currently under development. Sunagawa et al. [20] reported the efficacy of augmented reality in two case reports involving the extraction of impacted supernumerary teeth, and Liu et al. [21] described five pediatric cases using robotic-assisted extraction of completely impacted supernumerary teeth. These alternative approaches may offer potential advantages; however, these technologies are still under development with respect to accuracy, cost-effectiveness, and routine clinical applicability for extraction procedures. Future comparative studies directly comparing the surgical guide procedures with other guidance modalities would therefore be valuable.

Conclusion

The overall effect of the surgical guide system used in the present study was limited. However, the findings suggest that surgical guides may serve as a supportive safety tool in selected situations, particularly in more complex cases, by facilitating accurate identification of the extraction site and minimizing root damage through guidance of the bone removal direction. Future clinical control studies should continue to develop and evaluate surgical guides tailored to various cases to build a stronger evidence base.

Abbreviations

3D	three-dimensional
CT	computed tomography
STL	standard triangle language
IPA	isopropyl alcohol
iR	insufficient IPA rinsing
iP	insufficient postcure treatment
CHX	chlorhexidine disinfection
AC	autoclave sterilization
FBS	fetal bovine serum
CP	control plastic
SEM	scanning electron microscope
GA	general anesthesia
LA	local anesthesia

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-026-07994-4.

Supplementary Material 1.

Supplementary Material 2.

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Authors' contributions

Conceptualization: E.T., M.F-K. and T.S.; Methodology: M.F-K., M.K., and R.I.; Validation: N.M. and T.S.; Investigation: E.T., M.F-K., M.K., R.I., N.M. and A.M.; Data curation: E.T., M.F-K., M.K., and R.I.; Writing – original draft: E.T. and M.F-K.; Supervision: T.S.; All authors have read and approved the final version of the manuscript.

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Data availability

The datasets used and analyzed during the present study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The present clinical retrospective study and in vitro experimental study was approved by the ethical committee of the Nippon Dental University (NDU-T2021-19, NDU-T2021-29, respectively). All procedures involving human participants were conducted in accordance with the ethical standards of the institutional research committee. The study was carried out in compliance with the Declaration of Helsinki. All participants were fully informed of the experiment protocol of the study, the risks and benefits associated with participation prior to enrollment and their signatures and informed consent to participate were obtained.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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