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Accuracy of 3-dimensional surgical guide for endodontic microsurgery with a new design concept: A cadaver study

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Abstract

Aim: Despite the high success rate of endodontic microsurgery (EMS), it is difficult to suggest EMS as a general treatment option considering the difficulty of the procedure. A surgical guide has been proposed to overcome this problem. This study aimed to evaluate the stability of the surgical guide of a new design concept, as well as the accuracy of root resection, and to introduce the manufacturing method of the newly designed surgical guide.

Methodology: The experiment was conducted on 59 roots (9 in the maxillary and 50 in the mandibular region) of adult human cadavers. The surgical guide was designed using CAD/CAM design software based on cone-beam computed tomography (CBCT) images and optical scan files. Unlike conventional surgical guides, the surgical guide proposed herein was designed to act as a tooth-bone-supported removable appliance. Two different types of guides were prepared: the osteotomy guide (O guide) for separation of the cortical bone above the root tip with a trephine bur with an outer diameter of 6 mm and the root resection guide (R guide) for resection of the root tip with a trephine bur with an outer diameter of 4 mm. For stability evaluation, the guides were pressed at five predetermined locations after installation and checked for the presence of any movement. For accuracy evaluation, the length at which the root tip was cut was measured and examined by overlapping the preoperative and postoperative CBCT images.

Results: Of the 15 R guides, 14 were stably installed without mobility. For the R guide group, the root tip was resected with an average of 3.2 mm, showing better results than the no-guide group with an average of 4.0 mm.

Conclusions: The newly designed surgical guide of this study can be applied more stably, enabling root resection to be performed more accurately and simply according to the preoperative plan than when performed without a guide.

KEYWORDS

3D printing, CBCT, endodontic microsurgery, surgical guide

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INTRODUCTION

Nonsurgical root canal treatment (NSRCT) is a predictable treatment method with a high success rate of over 90%. However, failure was observed in approximately 10% of cases according to a study on the 5 years survival rate of NSRCT (Kwak et al., 2019). In cases where NSRCT fails or is contraindicated, apical surgery is a viable treatment option. Through apical surgery, one can extend the period of use of natural teeth, thereby improving the quality of life of patients (Fyffe & Kay, 1992; Gutmann & Harrison, 1985; Karabucak & Setzer, 2007).

Before the advancement of technology, the success rate of traditional apical surgery was approximately from 43.5% to 74% (Setzer et al., 2010). Recently, with the aid of advancements in technology, including enhanced magnification, illumination, microsurgical instruments and modern retro-filling materials, the efficiency and success rate of endodontic microsurgery (EMS) has increased significantly (Kim & Kratchman, 2006), with rates between 88.9% and 100% (Setzer et al., 2012). Despite the reported high success rate, not only general dentists but also endodontists often do not consider apical surgery as a treatment option because of the difficulty of the surgical procedures (Hull et al., 2003). The smaller the osteotomy performed, the more difficult it is to find the root apex in most posterior cases (Gutmann & Harrison, 1985). Accurate localization and precise resection of the root apex are critical for minimizing the destruction of the surrounding structures, resulting in positive outcomes with postoperative pain and better healing of the lesion (Strbac et al., 2017; von Arx et al., 2007). However, it is difficult to accurately recognize the location of the apical tip by relying solely on the reconstructed image of the cone-beam computed tomography (CBCT) scan. In addition, resecting the root of a certain length as planned by the operator during surgery without auxiliary equipment can be challenging (Ackerman et al., 2019; Fan et al., 2019).

To maintain the existing surgical method and to overcome the limitations of free-handed surgery, attempts are being made to create surgical guides using CBCT and optical scan data. Ahn et al. reported that when determining the location of the apex is difficult, a surgical guide is helpful for minimally invasive surgery (Ahn et al., 2018). In addition, Giacomino et al. introduced a successful one-step surgery using a surgical guide and a trephine bur (Giacomino et al., 2018). Other recent studies have shown that the utilization of a well-made surgical guide minimizes the destruction of adjacent structures and facilitates the localization of the root apex (Ackerman et al., 2019; Fan et al., 2019; Strbac et al., 2017).

Despite these efforts, surgical guides are not frequently utilized because of their lack of stability and accuracy. Most of the guides introduced so far are designed to rest on the crown of the tooth and its surrounding soft tissue. In actual clinical circumstances, the surgical guide is applied after flap elevation and thus must rest on the alveolar bone rather than the gingiva. Therefore, previous surgical guides, which are tooth-tissue-supported appliances, lack stability when applied after flap elevation because there is a gap between the guide and the alveolar bone. The new design concept of this study overcomes this limitation because the surgical guide used herein is a tooth-bone-supported appliance. With this new design, the entire guide is in contact with the hard tissue, and therefore, there is no movement of the guide when the guide is mounted. Digital impressions were obtained from the crown area, and the cortical bone surface was selectively used to reconstruct the CBCT images. The purpose of this study was to evaluate the stability and accuracy of a newly designed surgical guide that allows for a one-step operation.

MATERIALS AND METHODS

The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (Nagendrababu et al., 2021) (Figure 1).

One maxilla and four mandibles of adult human cadavers were obtained from the anatomy classroom of Yonsei University Dental College, Seoul, Korea. To calculate the appropriate sample size, a power analysis was performed, and the formula below which provides the sample size needed under the requirement of difference in mean and variance σ2 was used. The sample sizes for the experimental $p(x) = \frac{1}{\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$ group and the control group were planned at a ratio of 2:1.

Due to the lack of appropriate prior studies, a pilot study was conducted to obtain a difference in mean of 0.5 mm with a standard deviation of 0.6 mm for the calculation. Based on the pilot study, the necessary sample size was calculated to be 56. With a drop-out rate of 5%, considering the nature of the study using specimens from human cadavers, a total sample size was decided to use the measurement of 59 roots. SAS software, version 9.4 of the SAS system (SAS Institute Inc., Cary, NC, USA) was used to calculate the sample size. Therefore, a total of 59 roots (50 mandibular and nine maxillary roots) were included in this study.

For all specimens, preoperative CBCT (Rayscan Alpha plus: Ray Co., Ltd.) scans were obtained with a 0.23 mm

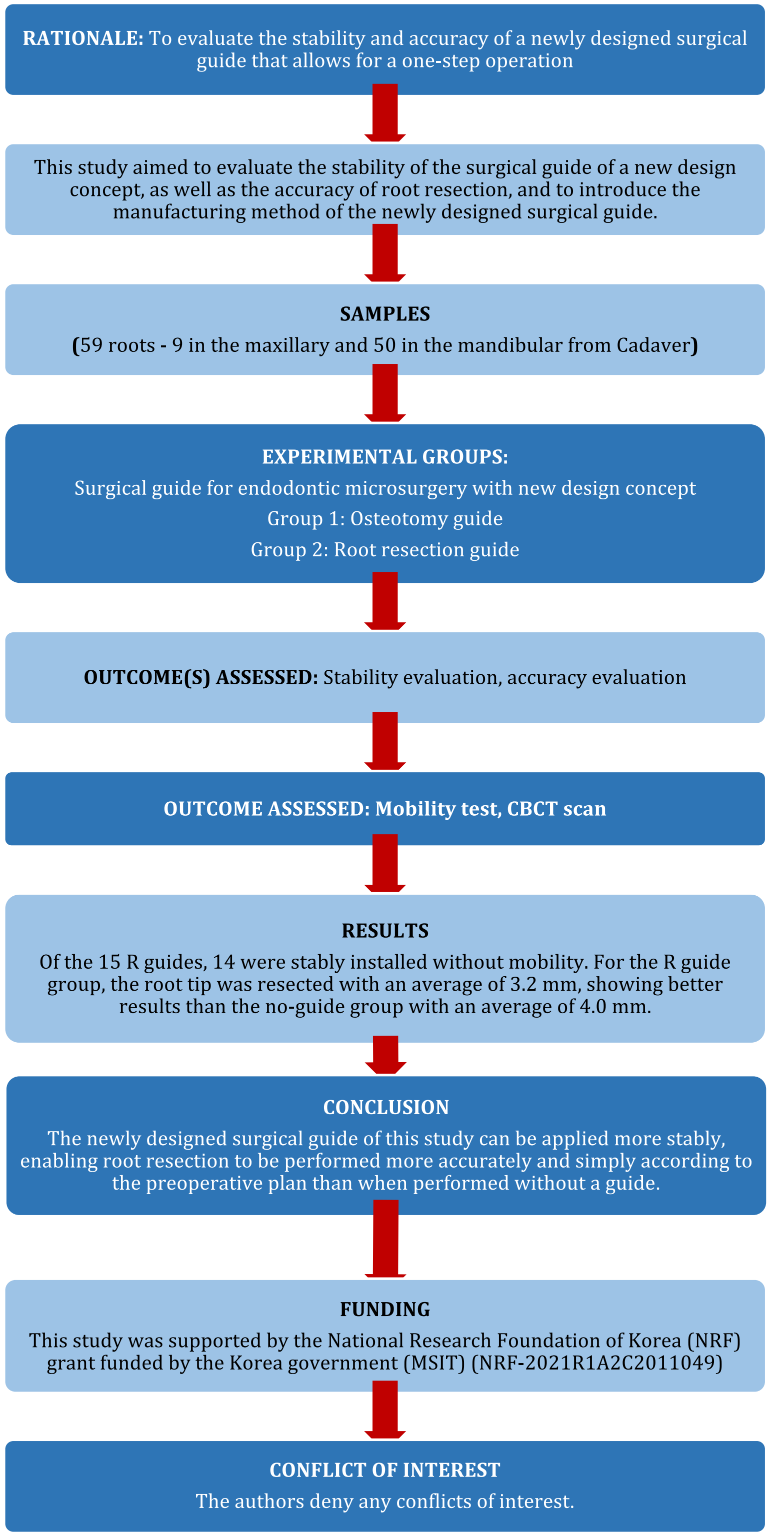

FIGURE 1 PRILE (2021) flowchart (Nagendrababu et al., 2021).

voxel size and the parameters were 90 kV and 12 mA with an exposure time of 14.0 s. Digital impressions of the coronal part of the teeth were obtained using a Trios chairside intraoral scanner (3Shape). Computer-aided design (CAD) planning and design software (EXOCAD: Exocad GmbH) was used to design the surgical guide. The guide was printed using resin (NextDent SG: NextDent BV) and a 3D printer (NextDent5100: 3D SYSTEMS). Trephine bur (Dentium) with outer diameters of 6 mm and 4 mm were used as cutting tools. Surgical guide design and production were performed by a single CAD software expert. All clinical procedures for both the experimental group and the control group were performed by a single, well-trained operator.

New design concept

The guide of this study was developed to cover the crown of the tooth and the surface of the cortical bone of the surgical site, using the previously proposed method (Figure 2a,b). This guide was designed to be in close contact with the surface of the cortical bone in consideration of flap elevation during the actual surgical procedure. The CBCT scan and the optical scan were superimposed so that the guide plate could be fabricated to rest above the cortical bone. As shown in (Figure 2c,d), a layer embodying the cortical bone was acquired from the CBCT scan, while the crown of the teeth was acquired from an optical scan. As shown in (Figure 2d), a guide was made using the superimposed image. Surgical guides made this way receive support only from hard tissues. Two types of guides were produced for this study: an osteotomy guide (O guide) and a root resection guide (R guide). The O guide was designed to perform osteotomy of the cortical bone with a 6 mm diameter. The R guide was designed for simultaneous osteotomy of the trabecular bone and root resection of 3 mm. In consideration of the clinical situation after flap elevation, all soft tissues of the maxillary/mandible specimen were removed before the use of the guide.

Stability evaluation

Fifteen R guides were used for stability evaluation. After applying the R guide to the specimen, it was checked for mobility when specific locations were pressed. The five compressed locations were as follows: in the regions where the cortical bone begins on the anterior and posterior borders of the guide, the anterior base region, the mid-base region and the posterior base region. A force of 20 N was applied parallel to the adjacent guide path. After the guide was pressurized at the five predetermined locations mentioned above, any mobility of 0.5 mm or more in any direction at any location was recorded as (+) and classified as a failure; otherwise, it was classified as a success and recorded as (−). Stability evaluation was performed by two examiners, and calibration was performed before

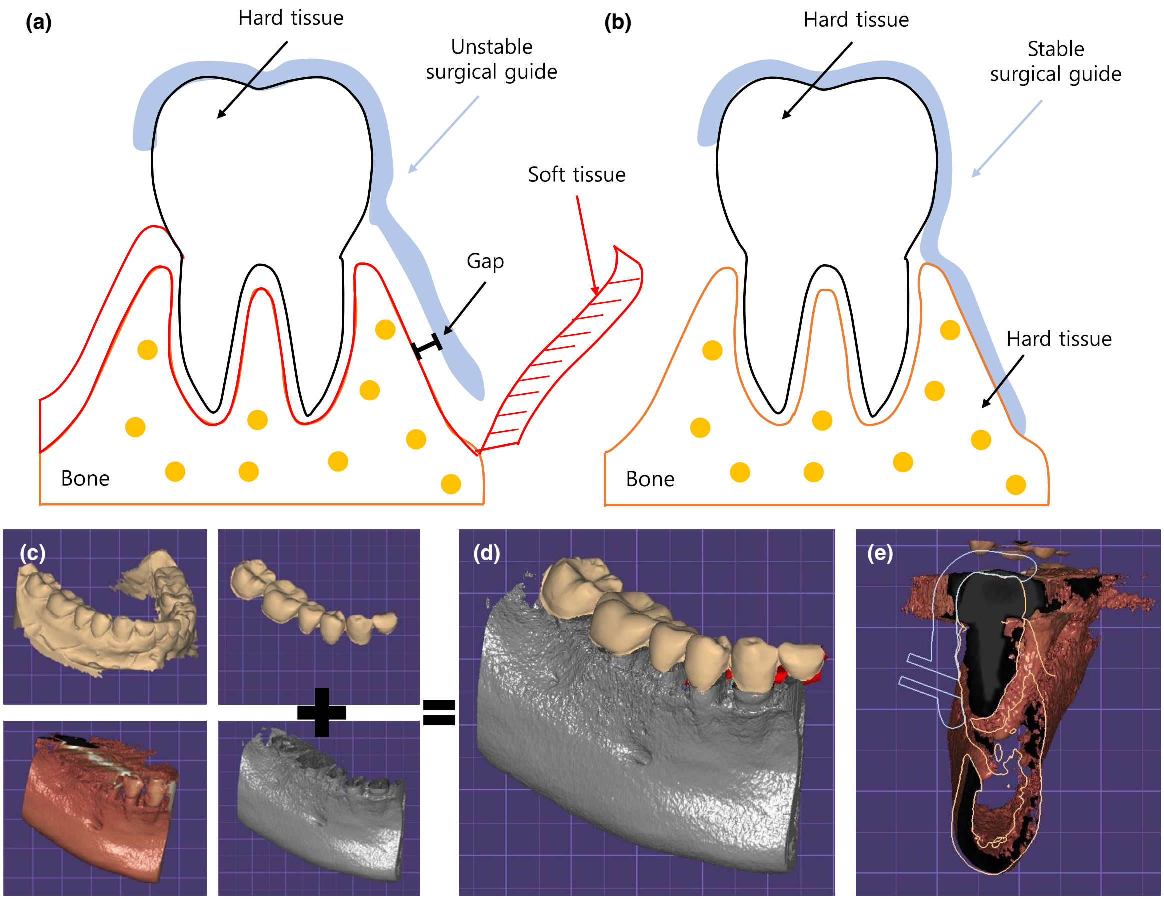

FIGURE 2 (a) Conventional concept; The surgical guide rests solely on the crown portion of the tooth. Other parts are manufactured based on the surface of the soft tissue. (b) New concept; The surgical guide rests on the crown portion of the tooth and the cortical bone right above the lesion. (c) The process of selecting the crown of the teeth from an optical impression and cortical bone from CBCT reconstructed image. (d) Example of the superimposed image of CBCT and optical scan. (e) Coronal slice of the tooth visualized in surgical planning software; the surgical guide was designed to be in close contact with the surface of the cortical bone and the crown of the tooth.

evaluation. When the two disagreed, repeated tests were conducted to reach an agreement.

Accuracy evaluation

To compare the accuracy of the new surgical guide with that of free-hand apical surgery, the following procedures were performed: For the experimental group, osteotomy of the cortical bone was performed in a circular shape using an O guide and a trephine bur with an outer diameter of 6 mm (Figure 3a–d,i,k). For the R guide group, the O guide was replaced with an R guide after removing the cortical bone. Following the preset guide path of the R guide, resection of the apical 3 mm and peri-root trabecular bone osteotomy were performed using a trephine bur with an outer diameter of 4 mm (Figure 3e–h,k–m). For the control group (no-guide group), after performing cortical bone osteotomy with an O guide, the distance from the cementoenamel junction(CEJ) to 3 mm above the root apex was calculated using a preoperative CBCT scan. The calculated length was measured with a periodontal probe for operator's best judgement, and 3 mm apical resection and trabecular bone osteotomy were performed using a trephine bur with an outer diameter of 4 mm without any surgical guide. The number of roots used in the experimental group was 41 (32 from the mandible and 9 from the maxilla), and the number of roots used in the no-guide group was 18 roots from the mandible.

After root resection, a postoperative CBCT scan was performed under the same conditions as the preoperative CBCT scan. By overlapping preoperative and postoperative CBCT scan images, the resected length of the root apex was measured using CAD software (EXOCAD, Exocad GmbH, Darmstadt, Germany). The resected length was defined as the distance from the root apex of the preoperative CBCT scan image to the centre of the resected plane of the postoperative CBCT scan image. A single-blinded evaluator measured the resected length twice at one-week interval to ensure an unbiased evaluation independent of previous assessments, and the average of the two values was used.

To evaluate the accuracy of the R guide, the measured values of the resected length of the mandibular roots were compared between the R guide group and the no-guide group. In addition, to examine whether there is a difference in the accuracy of the R guide according to the tooth position, the measured resected length was compared between the maxillary and mandibular arches, and among anterior, premolar and molar roots. Lastly, to confirm the clinical usefulness of the R guide, when the length of root resection was more than 2.5 mm and less than 3.5 mm, the guide was considered accurate, whereas when the length was less than 2.5 mm or over 3.5 mm, the guide was considered as inaccurate.

Statistical analysis

The evaluation of the mobility of the R guide was expressed as a percentile. For intraobserver reliability on evaluation of resected length, intraclass correlation coefficient (ICC) was calculated. The resected length was first analysed using the Shapiro–Wilk test and Kolmogorov–Smirnov test for normality of distribution. The Mann–Whitney test was used to evaluate the resected length of the R and no-guide groups. The Kruskal-Wallis test was used to compare the results depending on the tooth position in maxillary or mandibular arches and anterior, premolar and molar groups. All the statistical analyses were performed with SPSS Statistical Software version 25 (IBM Corp.), and $p < .05$ indicated statistical significance.

RESULTS

Stability evaluation

One of the 15 R guides showed mobility greater than 0.5 mm when the anterior base region and posterior base region were compressed with a force of 20 N and, therefore, was recorded as (+). The remaining 14 R guides showed no mobility and were recorded as (−) (Table 1).

Accuracy evaluation

Intraobserver reliability

The intraobserver reliability of the measurement of resected length showed ICC value of 0.926. ICC value showed that intraobserver reliability was excellent.

Evaluation of the overall accuracy of the R guide

The accuracy of the R guide was evaluated by analysing the length of the root resection. The resected length was 3.18 ± 0.26 mm (mean ± SD) in the R guide group. The average difference between the reference length of 3 mm and the actual resected length was 0.24 mm, indicating that the resection was performed within an error range of 1 mm (Figure 4a). The greatest resected length was 3.84 mm on the distobuccal root of the maxillary left second molar. The smallest resected length was 2.52 mm on the distal root of the mandibular left second molar. In terms of clinical usefulness, the R guide group had an accuracy of 92.7% (Table 2). Three cases of failure included maxillary first premolar, mandibular lateral incisor and distal root of a

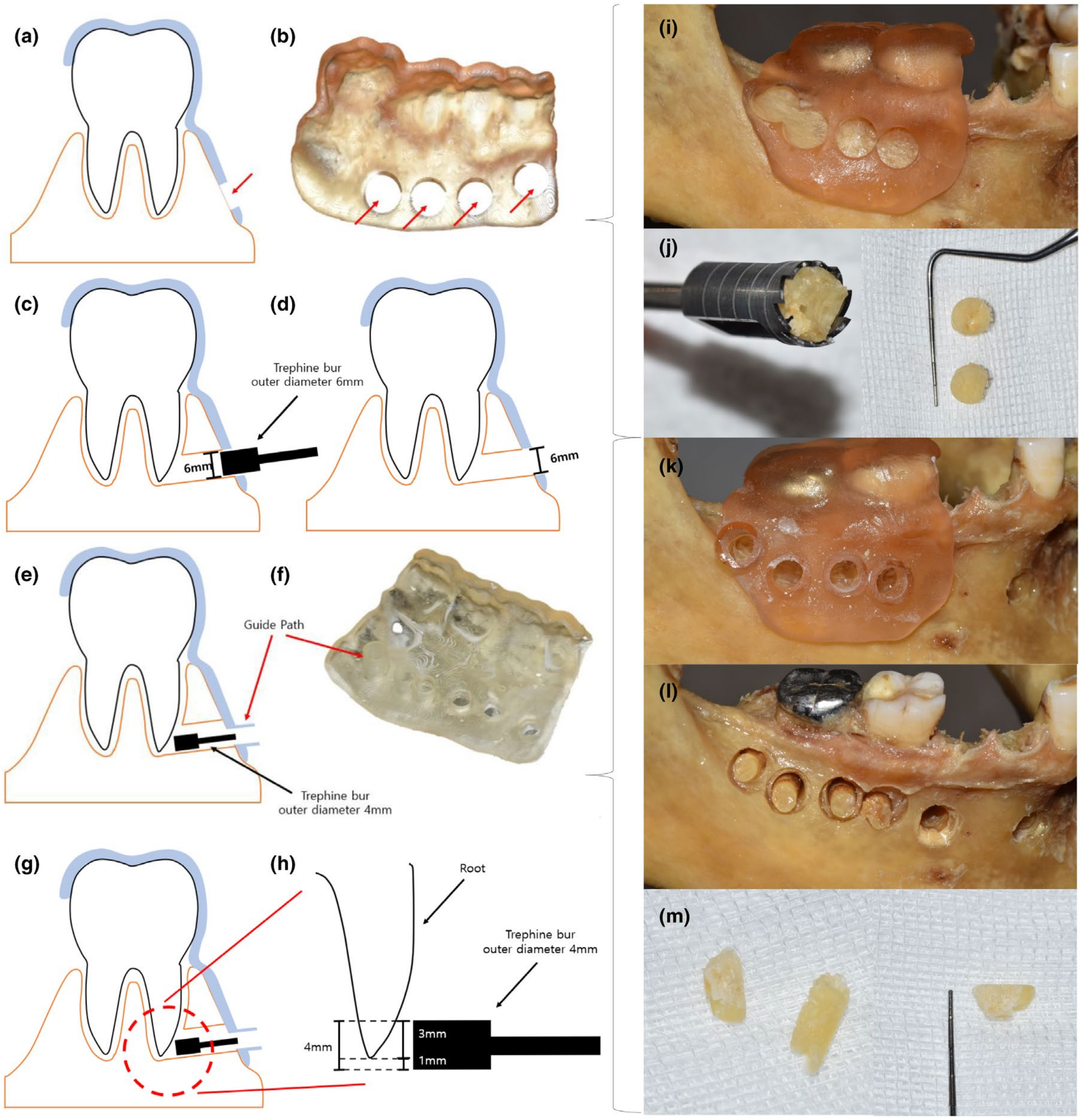

FIGURE 3 Schematic diagram and experimental process of osteotomy guide (O guide) and root resection guide (R guide). (a) Mounting O guide (b) O guide (c) Separation of cortical bone (d) Separated cortical bone; form 6 mm diameter hole (e) Mounting R guide (f) R guide (g,h) 3 mm root resection with trephine bur (i) Mandibular cadaver specimen with the 3D-printed osteotomy guide (j) Separating cortical bone with trephine bur (k) Mandibular cadaver specimen with the 3D-printed root resection guide (l) Resection root apex with trephine bur (m) Separated trabecular bone and root tip.

mandibular first molar with resected lengths of 3.59 mm, 3.71 mm, 3.84 mm, respectively.

Accuracy evaluation of R guide according to the arch

The results of resected length of maxillary and mandibular roots were compared within the experimental group. In the mandibular region, the mean value was 3.20 ± 0.24 mm, with a maximum of 3.84 mm and a minimum of 2.52 mm. In the maxillary region, the mean value was 3.11 ± 0.33 mm, with a maximum of 3.59 mm and a minimum of 2.53 mm. There were no statistically significant differences between the two regions (Figure 4b).

Accuracy evaluation of R guide according to the position of the tooth

The resected length of the experimental group was compared according to the position of the tooth. There were

7, 10 and 24 roots in the anterior, premolar and molar region, respectively. In the anterior region, the mean value was 3.22 ± 0.25 mm, with a maximum of 3.71 mm and a minimum of 3.01 mm. In the premolar region, the mean value was 3.19 ± 0.24 mm, with a maximum of 3.59 mm and a minimum of 2.84 mm. In the molar region, the mean value was 3.16 ± 0.27 mm, with a maximum of 3.84 mm and a minimum of 2.52 mm. There were no statistically significant differences among the three positions (Figure 4c).

TABLE 1 Evaluation of the stability.

R guide(Total $n=15$)	Stability, n (%)
(−)	14 (93.3)
(+)	1 (6.7)
Total	15 (100)

Note: (−): When the R guide is compressed at a predetermined location, it maintains a stationary state with zero mobility. (+): The R guide shows mobility when pressed at a predetermined location.

TABLE 2 A contingency table for the number of accurate and inaccurate procedures in the R guide group for all roots.

Clinical usefulness	n (%)
Accurate	38 (92.7)
Inaccurate	3 (7.3)
Total	41 (100)

R guide group vs. no-guide group

The mean resected length in the R guide group and the no-guide group was measured as 3.18 ± 0.24 mm and 4.00 ± 0.53 mm, respectively. These results were statistically significant ($p < .0001$) (Figure 4d). In terms of clinical usefulness, the no-guide group showed 16.7% accuracy, whereas R guide group showed 93.8% accuracy (Table 3).

TABLE 3 A contingency table for the number of accurate and inaccurate procedures of the *R* guide group and the no-guide group for mandible roots.

Clinical usefulness	R guide group (n, (%))	No-guide group (n, (%))
Accurate	30 (93.8)	3 (16.7)
Inaccurate	2 (6.2)	15 (83.3)
Total	32 (100)	18 (100)

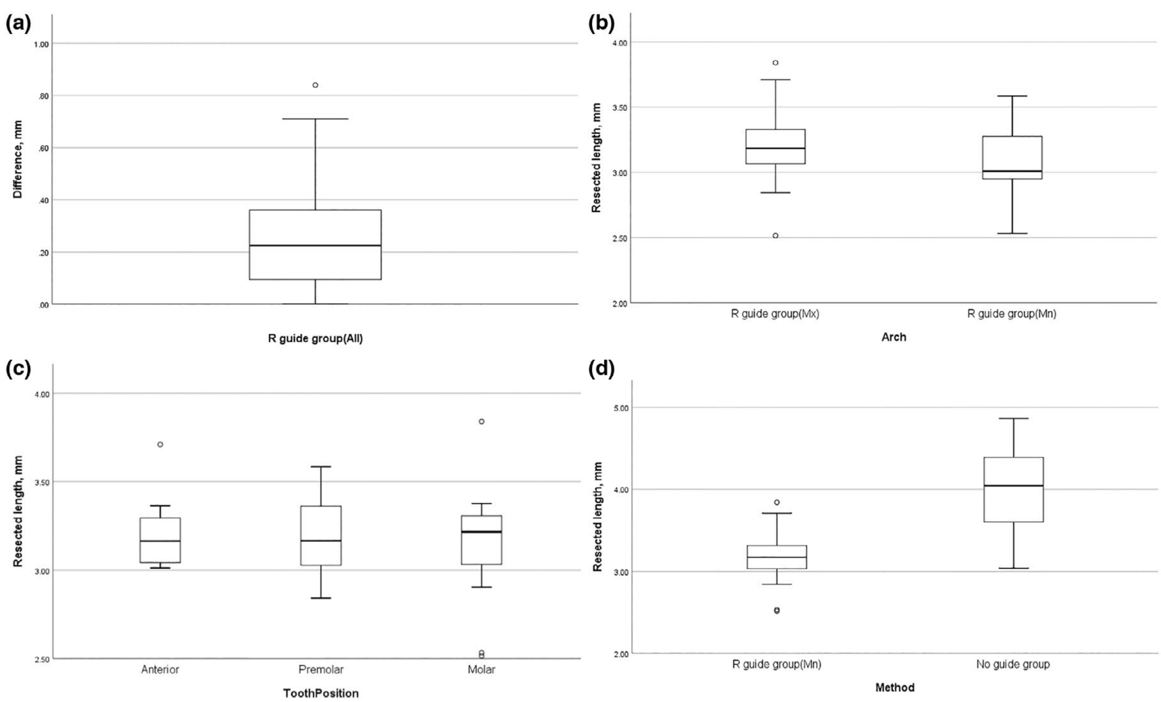

FIGURE 4 (a) A box plot of the difference between a preoperative plan (3 mm) and resected length for the R guide group including all roots. (b) A box plot of the resected root length for the maxilla and mandible group of the R guide group. (c) A box plot of the resected root length for the anterior, posterior and molar group of the R guide group. (d) A box plot depicting the mean (thick line), interquartile range (hinges) and extreme values (whiskers and open circles) of the resected root length for the R guide group and No-guide groups.

DISCUSSION

Customizing surgical guides through 3D planning for each patient is time-consuming and costly. However, considering the potential benefits of surgical guides, making a customized surgical guide for a patient is a meaningful task because it is very important to cut the root to the intended length while minimizing the destruction of the surrounding structures in the apical surgery (Iqbal et al., 2007). This can reduce irrelevant surgical exploration, thereby preventing iatrogenic damage to normal structures such as nerves and adjacent roots. In addition, with the aid of a surgical guide, one can reduce the time of operation while preserving the cortical bone. It was found that the length of the access window and the height of the remaining buccal bone plate may affect the postoperative prognosis of apical surgery (von Arx et al., 2007). Therefore, minimizing osteotomy through guided access can have a positive effect on the postoperative healing process.

Most of the previous studies focused on how well a surgical guide could locate the apex and adopted a conventional design concept that did not exclude the gingival tissue in the design process (Ackerman et al., 2019; Fan et al., 2019; Ray et al., 2020). In addition, the surgical guides used in previous studies considered the process of forming a window and the process of apex resection as one process and utilized only one surgical guide for the entire procedure (Giacomino et al., 2018). This study proposed a new design concept for a more stable application of the guide, and, therefore, two separate guides were fabricated. The O guide was produced and applied to separate the process of window formation from the root resection (Figure 3a–d,i,j). The experimental results were evaluated based on root resection rather than the apex location.

If the surgical guide is designed to rest on the gingival tissue, a gap will occur between the surgical guide and the cortical bone as much as the thickness of the elevated flap (Figure 2a). Unlike the conventional concept, the new design concept removes the gingival tissue of the operation site using CAD software before designing a surgical guide because when performing apical surgery, flap elevation is an important step that cannot be overlooked (Figure 2b).

Using the O guide, the rigid cortical bone can be initially removed to expose the relatively soft cancellous bone, thereby reducing pressure and damage to the periodontal tissue when resecting the root end (Figure 3i,l). This stepwise osteotomy also decreases the vibration generated during root resection, and with less vibration, the accuracy of the surgery improves. Furthermore, the cortical bone removed by forming a window (Figure 3j) can be used for autologous bone graft (Hirsch et al., 2016). Autologous bone grafting using cortical bone in the affected area can reduce postoperative discomfort (Del Fabbro et al., 2012) and is expected to aid in the healing of defects (Lin et al., 2010).

As for the one R guide with mobility (Table 1), an undercut occurred due to the complexity of the bone surface. The area with such complex anatomy was the anterior region of the mandible. The R guide with mobility was used to resect 3.71 mm of the mandibular lateral incisor, which deviates the most from the standard value of 3 mm among the anterior teeth (Figure 4c) and the second-longest in all teeth used in this study (Figure 4a). From these results, it can be seen that the use of a surgical guide without guaranteed stability can act as a factor that degrades the accuracy of apical surgery, even in the case of an anterior tooth.

Using R guide and a trephine bur with an outer diameter of 4 mm facilitates insertion of the ultrasonic tips and instruments needed for retro-preparation and retro-filling without additional osteotomy. Necessary amount of osteotomy and root resection can be performed predictably with minimal amount of deviation.

The R guide group showed better performance in both accuracy and precision than the no-guide group (Figure 4d). In general, the largest error was observed at the root of the rearmost molars (Figure 4c) because of the thicker buccal bone plate in these rearmost molars than the other teeth (Hargreaves et al., 2016). A larger error seemed to occur when thick bony tissue was present because the path provided by the R guide for the trephine bur was limited to the outside of the cortical bone, and the unsupported distance to reach the apex increased, resulting in more vibration. When the R guide was used, there was no statistically significant difference between the groups as a result of comparing the results according to the arch or tooth position (Figure 4b,c). This proves that it is possible to apply the surgical guide in all surgical cases.

The clinical usefulness of the new surgical guide was also evaluated (Table 3). Since 75% of canal aberrations are in the apical 3 mm, resection of the apical 3 mm can have a profound effect on the outcome of the surgery (De Deus, 1975). Therefore, it is important to evaluate whether the apical 3 mm can be resected using a surgical guide. While the no-guide group showed 16.7% accuracy, the R guide group showed 93.8% accuracy, proving the superiority of the surgical guide. However, the low accuracy of the no-guide group may be associated with the skill or habits of the operator. The difference in the resected length of the no-guide group was 1.02 mm on average based on the target value of 3 mm, but there were more cases in which the resected length was greater than 3.5 mm than shorter than 2.5 mm (Figure 4d). Nevertheless, the 0.5 mm leeway length proposed as the clinical usefulness evaluation criterion is a stricter criterion than the 1 mm leeway proposed by Ackerman (Ackerman et al., 2019), which is meant as a clinically significant value.

Besides the design proposed in this study, there may be various other methods of stabilizing a guided stent, such as cutting windows over the teeth to aid in positioning, or using bars to connect with the contralateral side. However, some of the methods often require additional imaging, which may not be desirable because it increases radiation exposure for the patient. Unlike such studies, the design applied in this study proposed a method that can produce a stable guide only with CBCT images taken for diagnosis, minimizing radiation exposure. In addition, the guide is designed to ensure maximum stability without being bulky and, therefore, is convenient to use during surgery.

Unfortunately, the no-guide group did not proceed entirely using the free-hand method. Instead, a trephine bur was used for root resection in both groups because this study focused on understanding the sole impact of the usage of a guide on the accuracy of root resection under the same cutting device. Moreover, to measure the root resection length blindly, preoperative and postoperative radiographic images were superimposed, requiring both the experimental and control groups to use the same cutting tool. It would have been beneficial if there was another group using completely free-hand method, but the number of samples was limited due to the nature of the experiment using cadaver.

Despite the limitations, the advantage of the guides used in this study is that it obtains stability through support from hard tissue. When applied clinically, slight modifications to the guide design may be necessary depending on the flap design used in the surgery. For example, when creating a guide for surgery with a papilla preservation flap, the designer should capture images of not only the tooth but also the papilla from the optical scan and capture images of hard tissue below the papilla from CBCT and then superimpose the two. Doing so will allow the operator to achieve support of the guide from the hard tissue despite the presence of soft tissue in the surgical site.

CONCLUSION

This study ensured the stability and accuracy of the new design concept of surgical guides. This design obtained support from hard tissues (teeth and alveolar bone) and thus resulted in better stability during surgical procedures. In addition, by creating two different types of guides (O guide and R guide), the operator ensured accurate amount of root resection with minimal damage. Further research is necessary to apply this guide design clinically in the future, and some design changes may be needed accordingly.

AUTHOR CONTRINUTIONS

Ha, Se-Won and Stephanie M Choi contributed equally to this work as first author. Ha, Se-Won: Writing—original draft preparation, investigation, resources. Choi, Stephanie Myeong: Writing—original draft preparation, data curation, formal analysis. Song, Minju: Writing—review and editing. Hu, Kyung-Seok: Writing—review and editing. Kim, Sunil: Writing—review and editing, conceptualization. Kim, Euiseong: Writing—review and editing, conceptualization, supervision, project.

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CONFLICT OF INTEREST STATEMENT

The authors deny any conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

This study was approved by the Institutional Review Board (IRB) of Yonsei University (IRB no. 2-2021-0078).

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