Zhou et al. BMC Oral Health (2025) 25:605
https://doi.org/10.1186/s12903-025-05939-x

BMC Oral Health

RESEARCH

Open Access

# Effect of 3D-printing assisted micro-osteoperforations on the rate of canine retraction: a clinical investigation

Yangyifan Zhou[1†], Qi Shao[1†], Miaomiao Bie[1], Jingju Zhang[2], Han Shi[2*†] and Feiwu Kang[1*†]

## Abstract

**Objectives** More time is often needed for adult orthodontic patients compared with juvenile counterparts due to lower tissue vitality. In some cases, the prolonged orthodontic treatment may cause a series of problems, such as enamel demineralization, dental caries, periodontitis and root resorption. Therefore, we aimed to accelerate tooth movement to avoid various adverse reactions by 3D-printing assisted micro-osteoperforations (MOPs) in difficult orthodontics cases.

**Methods** Twenty-eight adult patients (28.3 ± 3.4 years) with slow tooth movement after extraction of bilateral maxillary first premolars were included. The scheme of 3D-printing assisted MOPs was designed to perform bone punctures in the mesial and distal sides of canines.

**Results** The average speed of the retraction of canines was 1.02 ± 0.41 mm per month after MOPs and significantly faster than that before the MOPs, 0.34 ± 0.16 mm per month ($P < 0.05$). Moreover, the evaluation of side effects including root resorption, periodontal damage did not reach statistical difference and pain level was acceptable generally.

**Conclusion** MOPs assisted by 3D-printing could significantly accelerate tooth movement while achieving greater precision, without notably increasing side effects.

**Trial registration** ChiCTR2100044685, date of registration: 25/03/2021.

**Keywords** Micro-osteoperforations(MOPs), 3D-printing, Tooth movement, Adult orthodontics

[†]Yangyifan Zhou and Qi Shao contributed equally as first authors.

[†]Han Shi and Feiwu Kang contributed equally as corresponding authors.

*Correspondence:
Han Shi
shihan003@163.com
Feiwu Kang
kfw@tongji.edu.cn

[1]Shanghai Engineering Research Center of Tooth Restoration and Regeneration & Tongji Research Institute of Stomatology & Department of Department of Oral and Maxillofacial Surgery, Shanghai Tongji Stomatological Hospital and Dental School, Tongji University, No. 399, Middle Yan Chang Road, Shanghai 200072, China
[2]Shanghai Engineering Research Center of Tooth Restoration and Regeneration & Tongji Research Institute of Stomatology & Department of Orthodontics, Shanghai Tongji Stomatological Hospital and Dental School, Tongji University, No. 399, Middle Yan Chang Road, Shanghai 200072, China

## Introduction

The duration of comprehensive orthodontic treatment is usually 24–28 months in adults and primarily depends on the rate of orthodontic tooth movement [1]. Complicated reasons such as bone maturation, decreased mineral turnover, and patients' poor compliance with instructions for wearing orthodontic appliances can lead to the prolonged duration of treatment [2]. Unfortunately, the long-term orthodontic treatment may cause a series of other problems, such as dental caries, gingival recession, and root resorption [3], making the patient's compliance worse [4].

In these cases, orthodontists encounter difficulties in increasing the rate of orthodontic tooth movement and shortening the treatment time. At present, clinical methods for accelerating tooth movement include drugs treatment [5, 6], physical interventions [7, 8] and surgical aids [9–12]. Among these, the efficacy of surgical methods has been widely demonstrated in clinical practice. In 1893, Bryan first observed that corticotomy could accelerate the movement of teeth during orthodontic treatment [13]. Then, in 1959, Kole firstly put forth the hypothesis that the cortical bone of the alveolar bone was the source of resistance to tooth movement and by the disruption of its integrity, relatively independent bony blocks containing teeth could be formed, thus resulting in the acceleration of tooth movement [14]. Subsequently, the efficiency was tested by a series of researches [15, 16]. In a study conducted by Wilcko, it was found that localized corticotomy without the creation of an independent part for each tooth could also result in accelerated tooth movement [17]. Besides, he also claimed that the underlying mechanism was regional acceleratory phenomenon (RAP), which characterized by increased bone remodeling in injured areas. However, the wound caused by corticotomy had been a major side effect for orthodontic patients. Yaffle reported a procedure without flap surgery to make trauma to reduce the damage [18]. Afterwards, Dibart reported that piezocision defined by using piezoelectric devices to make trauma without flap elevation could also greatly optimize the procedure [19]. Along with the insight into the mechanisms, RAP, the surgical methods are becoming less and less invasive, as a result of which the MOPs technique has emerged as a promising method with minimal damage [20, 21]. Sufficient motivation is gained only through the drilling of holes around the teeth. Nevertheless, the technique still necessitates considerable surgical experience. In the absence of precise positioning of deep tissues, blind operations may result in damage to roots and other vital anatomical structures, including the maxillary sinus and neural tube.

For decades, engineers and dentists have tried hard to enhance the precision and reduce the trauma of the operation. Lately, with the development of digital manufacturing, 3D-printing technique is applied in a wider range of clinical settings to optimize the treatment [22, 23]. For example, recently, Shu reported that 3D-printing dental implants with modified layer activated blood clot formation, which contributed to a faster osseointegration speed [24]. Furthermore, the production of guide plates serves as an illustrative example of this trend. Milano was the inaugural researcher to utilize a 3D-printed guide plate in piezocision, which resulted in a reduction of trauma to periodontal tissue and enhanced precision [25]. Accordingly, the 3D-printing guide plate was introduced into this study with the objective of minimizing the side effects and enhancing the precision of MOPs operations.

Actually, the precise clinical outcome of MOPs with the assistance of a 3D-printed guide plate remains to be substantiated by robust clinical evidence. To ascertain whether this technique can expedite tooth movement and mitigate the risk of complications, further research is imperative. Accordingly, a clinical trial was devised to examine the rate of canine retraction with MOPs in adult patients whose teeth exhibit insufficient movement under conventional fixed appliance treatment. The null hypothesis is that micro-osteoperforations (MOPs) have no influence on the rate of canine retraction in adult cases. Furthermore, evaluations were conducted to assess the incidence of tooth root resorption, periodontal health, and the pain and discomfort experienced by patients throughout the course of treatment.

## Materials and methods

### Trial design

The sample size for this study was determined based on a type I error rate of 5% and a statistical power of 90% ($\beta = 0.1$, corresponding to a 1 - $\beta$ value of 0.9), as indicated by our pre-experiment data. The mean error value for the test group was determined to be $0.51 \pm 0.36$ mm. A sample size calculation conducted using SPSS 21.0 software indicated that a minimum of eight subjects was required to be included in the test group for the clinical investigation. In light of the anticipated subject shedding rate of no more than 20%, it was determined that a minimum of 10 subjects should be enrolled in the study to ensure an adequate sample size for meaningful analysis. This study was approved by the Ethics Committee of the Affiliated Stomatological Hospital (approval number: [2021]-SR-08). This study was conducted in accordance with the CONSORT guidelines. The registration number is as follows: The registration number for this study is ChiCTR2100044685, and it was registered on March 25, 2021. The name of the trial registry is as follows: The objective of this study is to examine the efficacy of micro-osteoperforation technology guided by a digital guide plate in accelerating orthodontic tooth movement.

### Participants, eligibility criteria, and settings

This prospective cohort study was conducted in the Department of Orthodontics and Oral and Maxillofacial Surgery of the Affiliated Stomatological Hospital from December, 2020 to November, 2023. All patients were in good general health with an age range of 18–45. Inclusion criteria included the following: (1) no systemic disease, (2) no history of periodontal therapy, (3) no radiographic evidence of periodontal bone loss, (4) no smoking, (5) no current active periodontal disease, (6) no gingivitis or untreated caries. Furthermore, all patients enrolled in the study exhibited a Class II Division 1 malocclusion, necessitating the removal of both maxillary first premolars. A senior orthodontist finished all the treatment and two experienced orthodontics residents calibrated the tooth movement and undertook other data collection and analysis. For orthodontic treatment, a series of arch wires, comprising 0.012, 0.016, 0.016 × 0.022, 0.016 × 0.025, 0.017 × 0.025, 0.018 × 0.025, and 0.019 × 0.025 NiTi (3 M, USA), were employed in a sequential manner, in conjunction with the orthodontic bracket (Damon Q, Ormco, USA), for the purpose of aligning and levelling the dentition. Subsequently, implant anchorage was employed to retract the anterior teeth as a unit, closing the gap on the 0.019 × 0.025 SS arch wire by 200 g of force with nickel-titanium coil springs (Shinye, China). The procedure for closing the tooth-extraction gap was all undertaken on 0.019 × 0.025 SS arch wire and obvious gap still remained after 6-month duration. The MOPs treatment was conducted at this time point. Then, patients still underwent the same closing-gap-treatment as aforementioned for another 3 months and were scheduled for follow-up visits at one-month intervals to monitor the force exerted by the springs and the condition of the appliances. The tooth movement rate was calculated by the change of the distance between canine and second premolar per month before and after surgery.

### Screening subjects

The clinical investigation was conducted in accordance with the ethical principles set forth in the Declaration of Helsinki by the World Medical Association. Prior to their participation, patients were informed of the details of the study, the potential risks, and the anticipated benefits. Each participant provided written consent. The investigation was subjected to a review and subsequently approved by the Ethics Committee of the Affiliated Stomatological Hospital. Initially, 34 adult patients with slow tooth movement after extraction of bilateral maxillary first premolars were included. Four patients were withdrew from the experiment, three of which did not participate in the study and one patient changed initial treatment plan. Two patients were lost to follow-up. The remaining 28 subjects started the experimental phase and completed the study, without any further subsequent loss.The mean age of the study subjects was 28.3 ± 3.4 years, and their demographic characteristics are presented in Table S1.

### Designing and building guides

In order to accurately and precisely elucidate the design of the MOPs treatment, we integrated the methodology of the digital guide plate with the objective of developing a novel design process for the MOPs digital guide plate, utilising CBCT and dentition scanning data (Medit i500, Korea). First, the CBCT data and dentition scanning data were aligned to create a high-resolution fitting model in Realguide 5.0 (Myray, Italy) (Fig. 1A). Subsequently, three 1.6 mm diameter holes were drilled on the mesial and distal sides of the canines respectively, as illustrated in the schematic diagram (Fig. 1B). The optimal depth of the holes was maintained at 7 mm, with a distance of at least 1 mm from the root of the tooth and 3 mm from the alveolar crest, as well as other crucial anatomical structures, including the maxillary sinus and nasal base. The configuration of the holes determined the design of the guide plate. The design was divided into two sections: the positioning and fixation of the guide plate by means of dentition and the functional component, which facilitates precise holing. The 3D direction of the hole was accurately positioned and adjusted from the sagittal, coronal, and anteroposterior sections of the CBCT in software to prevent damage to the roots of the teeth (Fig. 1C& Figure S1). Subsequently, the 3D guide plate was produced by using the 3D-printer (UltraCraft A2D, China) in accordance with the specifications set out in the software design (Fig. 1D). In the clinic, once the guide plate was in position, a high-speed turbine was used to drill and control the depth of the hole along the length of the needle, thereby completing MOPs cases and continuing orthodontic space closure without delay (Fig. 1D). Following the surgical procedure, the accuracy of the technique was assessed using cone beam computed tomography (CBCT), which demonstrated that the discrepancy between the actual angle achieved through clinical drilling and the intended angle was no greater than 5° (Fig. 1E). Additionally, it was observed that the formation of scar tissue on the mucosal surface at the three-month mark post-surgery was not as pronounced as in traditional surgical techniques that accelerate orthodontic tooth movement. This finding highlights the minimally invasive nature of this technology (Fig. 1F). Collectively, these results indicate that the technology of 3D-printing assisted MOPs has the advantages of precision and minimal invasion, which is conducive to precise clinical treatment and the popularization of this technology.

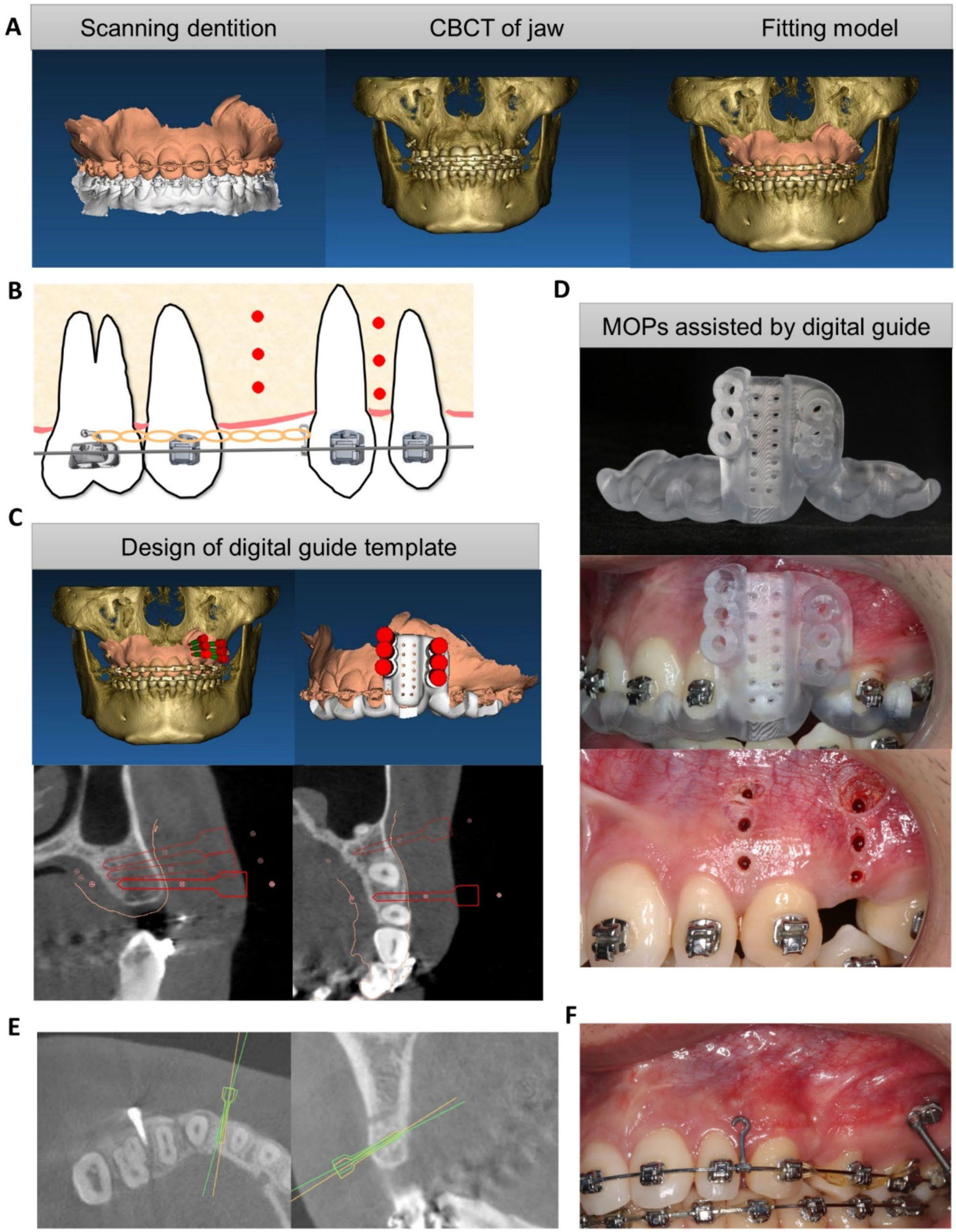


**Fig. 1** The design and process of MOPs. (**A**) CBCT data and hard tissue scanning dentition data were fitted together in a point-to-point manner in Real-guide 5.0. (**B**) Schematic diagram showed the position of punching hole. (**C**) The design of digital guide template was shown and the drill position was drawn in red. (**D**) MOPs was carried out under the guidance of digital guide template. (**E**) CBCT showed the designed drill angle in green lines and the actual drill angle in yellow lines. (**F**) Intraoral soft tissue recovery at 3 months after MOPs

### Surgical procedure

The patient underwent MOPs in accordance with the prefabricated 3D guide plate. The surgical instruments utilized in this procedure included a high-speed dental air turbine handpiece (Pana-Max2 M4, NSK, Japan) and carbide burs (H33L.316.016, Gebr. Brasseler, Germany). The drilling depth was 7 mm, and the operation was completed by the same surgeon. Immediately following the surgical procedure, orthodontic treatment was initiated to close the gap, utilizing a straight wire with a force of 200 g. Anterior retraction was achieved through the use of calibrated 200-g nickel-titanium coil springs (Shinye, China), which were connected from mini-implants (Cibei, Ningbo, China) to orthodontic hooks on arch wires. At each visit, the force of the coil was evaluated, and any modifications to the appliances were documented. The patient was counseled to refrain from self-administering painkillers unless medically indicated. The primary observational criteria were the rate of tooth movement, tooth root resorption, periodontal health, and pain level.

### Observation index

At the outset of the orthodontic treatment, on the day of surgery, and on a monthly basis for a period of three months following surgery, oral scanning was conducted to quantify tooth movement. All scans were imported as. STL files into Medit Design software (Medit, Korea). Three reference points were placed on the rugae of each palate, since these are considered most stable during OTM [26]. After this initial check, a distance map with color coding was created to assess the stability of the area for superimposition (Fig. 2A). Between each time point, points set in the same position of the canines can be used by the software to automatically calculate the distance of tooth movement. Additionally, three CBCT scans were conducted at the outset of the orthodontic treatment, on the day of surgery, and at the end of the observation period. The pre-MOPs and post-MOPs data pertaining to jaw and dentition fitting were imported as STL files into Mimics 21.0 software (IBM, Armonk, NY) (Fig. 2B). As described by Chen et al., the 3D reconstruction of the target tooth was performed by setting three orthogonal sections: sagittal, coronal, and cross Sect [27]. Landmark of CBCT for root length was designated on the 2D surface in Mimics 21.0 software (Fig. 2C). The measurements of root volume were shown in Fig. 2D. Subsequently, periodontal conditions were evaluated, including PLI, PD, and CAL, on the day of surgery and at the end of the observation period. The patients' pain levels were assessed at one week post-operatively. The participants were asked to assess their level of pain on the day of surgery, subsequently at 1 h, 3 h, 7 h, 24 h, 3 days, 5 days, and 7 days after canine retraction with a numeric rating scale. The patients were instructed to select a number from the provided table, which ranged from 0 to 10, to indicate the intensity of their pain, with 0 indicating no pain and 10 indicating the worst possible pain.

### Statistical analysis

The data were presented in the form of means ± standard error of the mean (SEM) and all statistical analyses were performed using GraphPad Prism 10 (GraphPad Software, USA). A Student's t-test was employed to ascertain any significant differences between the two groups and one way ANOVA test was used among 3 or more groups. A $p$-value of less than 0.05 was deemed statistically significant.

## Results

### The speed of tooth movement before and after MOPs

After MOPs surgery, the speed of tooth movement was significantly increased. As shown in Fig. 3A, the average adduction speed of the canine was 0.34 ± 0.16 mm/month before MOPs and 1.02 ± 0.41 mm/month after MOPs ($P < 0.05$), indicating that the utilization of MOPs could markedly enhance the speed of tooth movement (Fig. 3A).

### Monthly tooth movement after MOPs

As illustrated in Fig. 3B, a normality test revealed that the tooth movement rate at various time points following MOPs did not adhere to a normal distribution, as compared to the preoperative baseline. Subsequently, the Wilcoxon test for paired samples was employed. The tooth movement rate before surgery was 0.34 ± 0.16 mm. It reached 0.90 ± 0.65 mm at the first postoperative month, while the second and third postoperative months exhibited rates of 1.14 ± 0.50 mm and 1.07 ± 0.54 mm respectively. A comparison of the preoperative rate of 0.34 mm with the subsequent rates revealed statistically significant differences ($P < 0.05$). In general, the tooth movement of patients within three months after MOPs surgery was significantly faster than that observed prior to surgery. The movement rate of the first month after surgery exhibited notable discrepancies among subjects, indicating a difference in tissue responsiveness. Furthermore, although no significant difference was observed, the tooth movement velocity was the most rapid in the second month following surgery. Finally, in the final month of observation, MOPs were still able to significantly accelerate the speed of tooth movement.

### Root resorption

As illustrated in Fig. 3C, the mean length of root resorption in the canine after MOPs surgery (2.13 mm) did not exhibit a statistically significant discrepancy compared to the pre-MOPs measurement (1.96 mm). This finding was

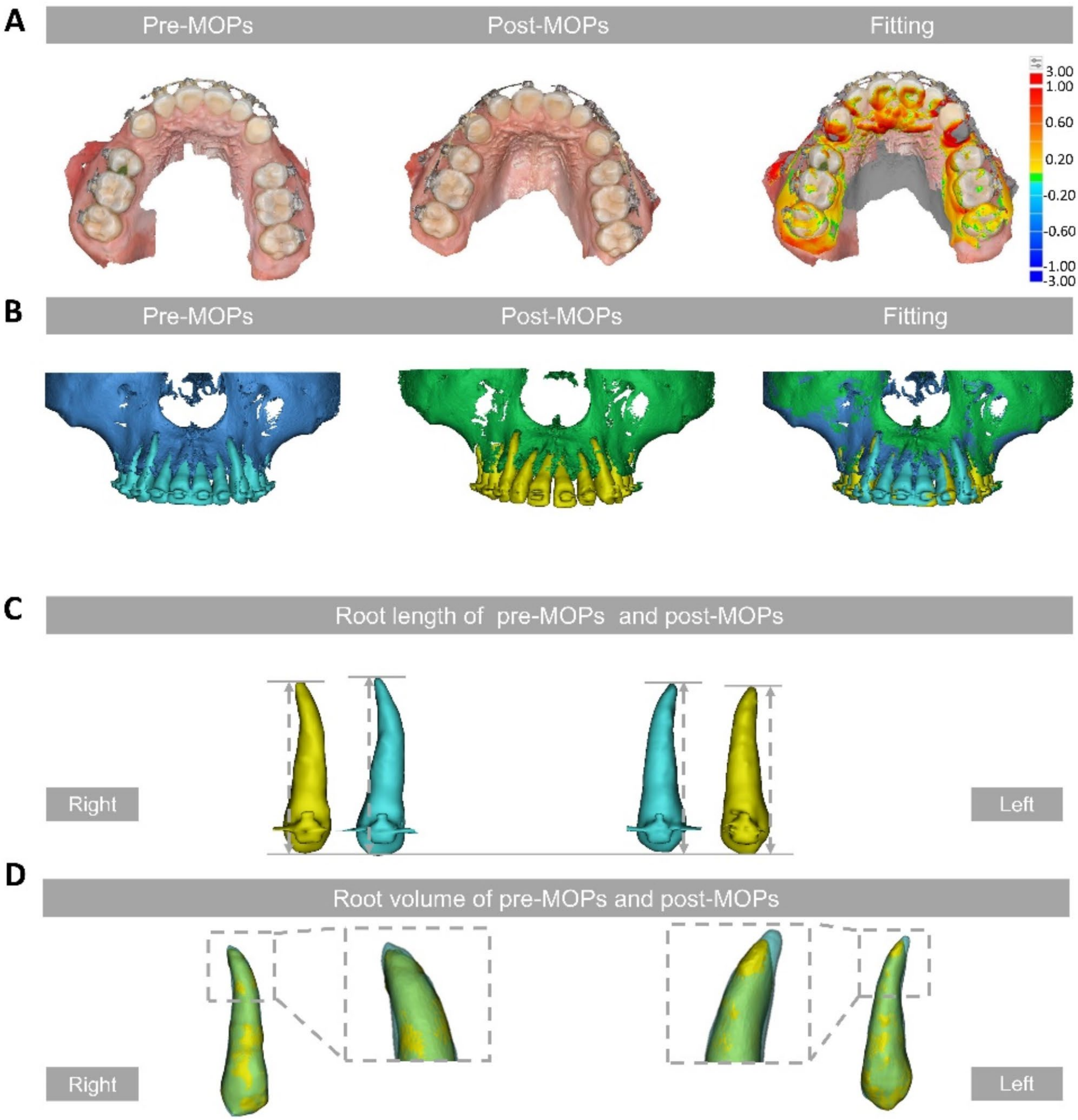


**Fig. 2** Oral scanning and CBCT data fitting of pre-MOPs and post-MOPs. (**A**) The representative pictures of oral scanning and their fitting results. (**B**) The representative pictures of the 3D reconstruction of maxillae. (**C**) The changes in root length of canines. (**D**) The changes in root volume of canines

further substantiated by the analysis of the volume of root resorption (Fig. 3D). The mean volume of root resorption in the canine group following MOPs was 49.15 $mm^3$, while the mean volume of root resorption in the control group was 55.13 $mm^3$. Moreover, the statistical analysis of the root length before and after MOPs is presented in Fig. 3E. The mean root lengths were $11.56 \pm 0.07$ mm for the lateral incisors, $13.60 \pm 0.04$ mm for the canines, and $12.43 \pm 0.06$ mm for the second premolars prior to the surgical procedure. The root lengths for the final three-month period were $11.53 \pm 0.07$ mm for the lateral incisors, $13.26 \pm 0.09$ mm for the canines, and $12.36 \pm 0.06$ mm for the second premolars. A comparison of the lengths of the roots before and after the operation revealed that, three months after MOPs, the roots of the lateral incisor, canine, and second premolar had all undergone resorption; however, no statistically significant difference was observed ($P > 0.05$). In conclusion,

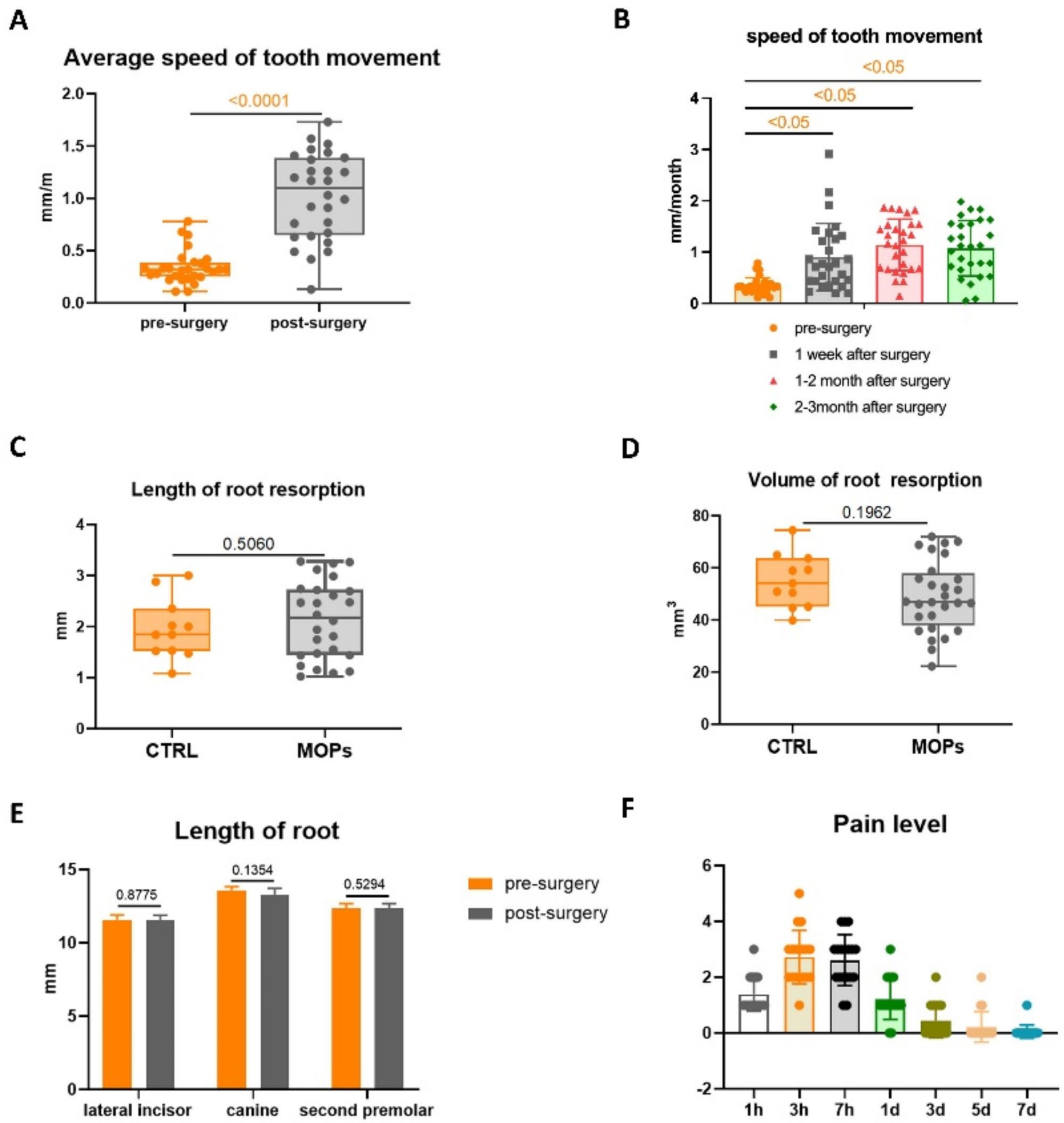


**Fig. 3** Statistical analysis of tooth movement and side effects. (**A**) Comparison of tooth movement average speed before and after MOPs. (**B**) Tooth movement speed at different periods before and after MOPs. (**C**) The comparison of root resorption length between MOPs group and control group. (**D**) The comparison of root resorption volume between MOPs group and control group. (**E**) MOPs comparison of root length of lateral incisors, canines and second premolars. (**F**) The degree of pain in different periods of one week after surgery. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$)

the application of MOPs in orthodontic tooth movement may result in root resorption of the canine tooth.

### Periodontal conditions

To assess the periodontal status throughout the course of treatment, three widely accepted indicators were employed. The results demonstrated that there was no statistically significant difference between the pre-MOPs and post-MOPs in terms of PLI, PD, and CAL. This finding suggests that the MOPs and relevant orthodontic treatment did not result in any discernible periodontal damage (Fig. 4; Table 1).

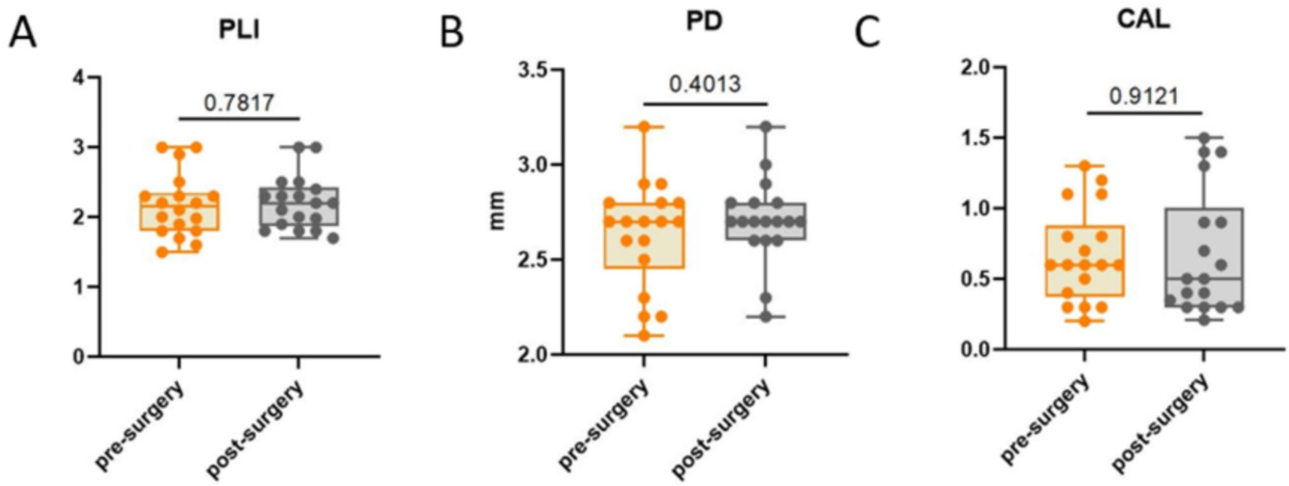


**Fig. 4** Periodontal studies after 3D-printing assisted MOPs. (**A**) The statistical analysis of PLI of patients in stages of pre-surgery and post-surgery; (**B**) The statistical analysis of PD of patients in stages of pre-surgery and post-surgery; (**C**) The statistical analysis of CAL of patients in stages of pre-surgery and post-surgery

**Table 1** Comparison of preoperative and postoperative periodontal health

| Group | PLI | PD(mm) | CAL(mm) |
|---|---|---|---|
| Preoperative | 2.17 ± 0.11 | 2.63 ± 0.07 | 0.67 ± 0.08 |
| Postoperative | 2.21 ± 0.09 | 2.71 ± 0.05 | 0.68 ± 0.10 |
| *p* | 0.7817 | 0.4013 | 0.9121 |

### Pain level

As illustrated in Fig. 3F, the pain levels of patients across different time points post-operatively did not adhere to a normal distribution, as indicated by the median (25%, 75%) following a normality test. The results demonstrated that the pain level reached its peak on the first day following the operation, with the most severe pain occurring between three and seven hours post-operatively. However, the majority of patients reported experiencing only mild pain. During the postoperative follow-up period, patients indicated that the degree of pain was acceptable for them to tolerate without the need for analgesics.

## Discussion

One of the primary challenges in orthodontic treatment is the prolonged duration, which is associated with an increased risk and severity of adverse reactions. Prolonged treatment times are directly linked to complications such as root resorption, dental caries, periodontal issues, and soft tissue injuries. Consequently, reducing treatment duration has been a key focus for clinicians and researchers.

Surgical interventions have demonstrated the most significant and reliable impact on accelerating orthodontic tooth movement. However, traditional surgical techniques, such as osteotomy involving mucoperiosteal flaps, are rarely used due to their association with postoperative pain, swelling, and low patient acceptance. Less invasive procedures, such as piezocision [28, 29] and corticision [30, 31], target the cortical bone without requiring flap elevation, offering an alternative approach.

Micro-osteoperforation (MOP), in contrast, addresses many limitations of traditional surgical methods. It can be performed independently by orthodontists, facilitating tooth movement and simplifying complex orthodontic treatments. Despite these advantages, prior studies have not adequately examined factors such as periodontal status, root resorption, and the duration of acceleration effects in adult patients.

In this study, we comprehensively evaluated the clinical efficacy and potential side effects of MOP. Patients undergoing MOP demonstrated a significantly higher rate of tooth movement, with a post-procedure rate of 1.02 ± 0.41 mm/month compared to the pre-procedure rate of 0.34 ± 0.16 mm/month. These findings confirm the effectiveness of MOP, with results lasting up to three months, consistent with previous studies [20, 21]. However, the duration of sustained effectiveness extended beyond the observation period of this study and requires further investigation in subsequent research.

Our findings indicate that 3D digital guides significantly reduce trauma, improve the accuracy of micro-osteoperforations (MOPs), and simplify the procedure. Postoperative wounds are minimal and suture-free, resulting in manageable pain levels that are well-tolerated by patients. Additionally, the healed scars are unobtrusive and do not cause discomfort. The digital simulation design effectively controls the direction and depth of perforations, thereby avoiding damage to tooth roots and critical anatomical structures. Immediate postoperative cone-beam computed tomography (CBCT) imaging confirmed that no dental tissue damage occurred in any patient, demonstrating the high precision of 3D guide-assisted MOPs.

Given that MOPs are performed through soft tissues, periodontal complications from soft tissue or localized bone damage are a concern. To minimize these risks, the perforation design ensured that the lowermost hole was positioned at least 3 mm from the alveolar crest, reducing gingival papilla irritation and minimizing the likelihood of black triangle. Periodontal assessments after MOPs, including probing depth (PD), clinical attachment level (CAL), and plaque index (PLI), showed no significant differences compared to baseline, confirming that the procedure did not cause additional damage to the hard or soft tissues surrounding the tooth roots. Collectively, our evaluation is consistent with previous studies in terms of exerting little influence on the periodontal tissues [32, 33].

Root resorption is a common complication of orthodontic treatment [3, 34]. While most cases are clinically insignificant, severe root resorption can compromise dental health. Previous studies have attributed root resorption to factors such as patient age, gender, treatment method, and duration [35, 36], though conclusions remain inconsistent. Canine root resorption, in particular, may be associated with their greater movement during treatment and the localized bone acceleration, which recruits osteoclasts, cytokines, and inflammatory markers.

In this study, despite the accelerated tooth movement observed with 3D guide-assisted MOPs, there was no significant increase in root resorption. This suggests that MOPs not only enhance treatment efficiency but also maintain periodontal safety, indicating a broad applicability for this technique.

Existing studies have demonstrated that the mechanism by which jaw surgeries, including micro-osteoperforations (MOPs), accelerate orthodontic tooth movement is the regional acceleratory phenomenon (RAP). This phenomenon occurs when localized soft and hard tissue trauma alters the microenvironment, triggering osteoclastic and osteogenic activity in adjacent tissues through cellular regulatory mechanisms. This process accelerates bone resorption and synthesis, leading to rapid remodeling of the hard and soft tissues. These changes include ischemic, hypoxic, and inflammatory alterations.

Bone remodeling is inherently an inflammatory process mediated by the expression of cytokines and inflammatory markers. In RAP, cortical bone surgery intensifies aseptic inflammatory responses in local tissues. Following osteocorticotomy, the early stages of alveolar bone healing are characterized by the infiltration of numerous inflammatory cells, which produce various inflammatory cytokines [37]. For instance, in a rabbit model simulating orthognathic surgery, levels of interleukin-6 (IL-6), interleukin-1β (IL-1β), and tumor necrosis factor-α (TNF-α) were elevated from 3 to 14 days post-surgery, indicating that surgical trauma induces changes in inflammatory factor expression [38].

Pro-inflammatory factors such as TNF-α, IL-1, IL-6, IL-11, and IL-17 play a pivotal role in promoting bone resorption by enhancing osteoclast differentiation and activity while inhibiting osteoblast differentiation [39]. TNF-α and IL-1 synergistically promote osteoclastogenesis, directly or indirectly, by stimulating the expression of receptor activator of nuclear factor kappa-B ligand (RANKL) in osteoblasts and fibroblasts, while down-regulating osteoprotegerin (OPG) [40, 41]. IL-6 not only promotes osteoclast formation by directly interacting with osteoclast precursors but also enhances osteoblast-mediated osteoclast differentiation through activation of the JAK2/STAT3 signaling pathway and upregulation of RANKL expression [42].

Hypoxia-inducible factor (HIF) plays a crucial role in the cellular response to hypoxic microenvironments. Experimental studies have shown that mandibular osteotomy-induced hypoxia activates HIF-1α expression in osteoblasts, enhancing glycolysis-driven acid production [43]. This promotes osteoclast activity and accelerates bone resorption. Conversely, HIF-1α gene knockdown significantly reduced bone resorption in the first molar region of mice post-mandibular osteotomy, attenuating the RAP effect [44].

These findings elucidate the cellular and molecular mechanisms underlying MOPs and provide a theoretical foundation for their scientific application in accelerating orthodontic tooth movement.

## Conclusion

In this study, we proved that 3D-printing assisted MOPs could speed up tooth movement significantly and safely in adult patients. Furthermore, there were no significant side effects such as pain and root resorption when compared to traditional orthodontic treatment. Thus, our study provides a new adjunctive method for orthodontic treatment and sheds light on minimizing the potential side effects of adult patients by shortening the duration of orthodontic treatment. Future studies are necessary to investigate the effect of MOPs on a multi-centered level.

### Abbreviations

| | |
|---|---|
| MOPs | Micro-osteoperforations |
| CBCT | Cone beam computed tomography |
| RAP | Regional acceleratory phenomenon |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-05939-x.

Supplementary Material 1

**Acknowledgements**
We greatly appreciate Tairan Wang and Chunan Cheng for their help in the study.

**Author contributions**
Y.Z. and Q.S. wrote the main manuscript text, M.B. and J.Z. prepared Figs. 1, 2 and 3. H.S. and F.K. reviewed the manuscript.

**Funding**
Financial support was provided by Shenkang Hospital Development Center of Shanghai (Grant No. SHDC12024119).

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

## Declarations

**Ethics approval and consent to participate**
This study was approved by the Ethics Committee of the Affiliated Stomatological Hospital (approval number: [2021]-SR-08). The study has conducted according to the principles of the Declaration of Helsinki. Written informed consent was obtained from all of the participants in the study. This study was conducted in accordance with the CONSORT guidelines.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

**Clinical trial number**
ChiCTR2100044685.

Received: 10 August 2024 / Accepted: 2 April 2025
Published online: 20 April 2025

**References**

1. Krishna VB, Duggal I, Sharan J, Mangaraj M, Duggal R, Jena AK. Effect of leukocyte-platelet-rich fibrin (L-PRF) on the rate of orthodontic tooth movement and expression of various biomarkers in gingival crevicular fluid. Clin Oral Investig. 2023;27(5):2311–19.
2. Clark RL, Schneider M, Mahmoudi T, Bashirelahi N. What every dentist and patient should know about accelerated orthodontic tooth movement. Gen Dent. 2018;66(4):16–20.
3. Sameshima GT, Iglesias-Linares A. Orthodontic root resorption. J World Federation Orthodontists. 2021;10(4):135–43.
4. Pachêco-Pereira C, Pereira JR, Dick BD, Perez A, Flores-Mir C. Factors associated with patient and parent satisfaction after orthodontic treatment: a systematic review. Am J Orthod Dentofac Orthop. 2015;148(4):652–9.
5. Bartzela T, Türp JC, Motschall E, Maltha JC. Medication effects on the rate of orthodontic tooth movement: a systematic literature review. Am J Orthod Dentofac Orthop. 2009;135(1):16–26.
6. Tyrovola JB, Spyropoulos MN. Effects of drugs and systemic factors on orthodontic treatment. Quintessence Int. 2001;32(5):365–71.
7. Krishnan V, Davidovitch Z. On a path to unfolding the biological mechanisms of orthodontic tooth movement. J Dent Res. 2009;88(7):597–608.
8. Milligan M, Arudchelvan Y, Gong SG. Effects of two wattages of low-level laser therapy on orthodontic tooth movement. Arch Oral Biol. 2017;80:62–8.
9. Hassan AH, Al-Saeed SH, Al-Maghlouth BA, Bahammam MA, Linjawi AI, El-Bialy TH. Corticotomy-assisted orthodontic treatment. A systematic review of the biological basis and clinical effectiveness. Saudi Med J. 2015;36(7):794–801.
10. Teng GY, Liou EJ. Interdental osteotomies induce regional acceleratory phenomenon and accelerate orthodontic tooth movement. J Oral Maxillofac Surg. 2014;72(1):19–29.
11. Wilcko W, Wilcko MT. Accelerating tooth movement: the case for corticotomy-induced orthodontics. Am J Orthod Dentofac Orthop. 2013;144(1):4–12.
12. Yavuz MC, Sunar O, Buyuk SK, Kantarcı A. Comparison of piezocision and Discision methods in orthodontic treatment. Prog Orthod. 2018;19(1):44.
13. Frost HM. The biology of fracture healing. An overview for clinicians. Part I. Clin Orthop Relat Res. 1989;248:283–93.
14. Kole H. Surgical operations on the alveolar ridge to correct occlusal abnormalities. Oral Surg Oral Med Oral Pathol. 1959;12(3):277–contd288.
15. Generson RM, Porter JM, Zell A, Stratigos GT. Combined surgical and orthodontic management of anterior open bite using corticotomy. J Oral Surg. 1978;36:216–9.
16. Gantes B, Rathbun E, Anholm M. Effects on the periodontium following corticotomy-facilitated orthodontics. Case Rep J Periodontol. 1990;61:234–8.
17. Wilcko MT, Wilcko WM, Pulver JJ, et al. Accelerated osteogenic orthodontics technique: A 1-stage surgically facilitated rapid orthodontic technique with alveolar augmentation. J Oral Maxillofac Surg. 2009;67(10):2149–59.
18. Yaffe A, Fine N, Binderman I. Regional accelerated phenomenon in the mandible following mucoperiosteal flap surgery. J Periodontol. 1994;65:79–83.
19. Dibart S, Sebaoun JD, Surmenian J. Piezocision: a minimally invasive, periodontally accelerated orthodontic tooth movement procedure. Compend Contin Educ Dent. 2009;30(6):342–4.
20. Alikhani M, Raptis M, Zoldan B, Sangsuwon C, Lee YB, Alyami B, et al. Effect of micro-osteoperforations on the rate of tooth movement. Am J Orthod Dentofac Orthop. 2013;144:639–48.
21. Eid FY, El-Kenany WA, El-Kalza AR. Effect of micro-osteoperforations on the rate of canine Retraction: a split-mouth randomized controlled clinical trial. Egypt Orthodontic J 2018;52.2.
22. Targońska S, Dobrzyńska-Mizera M, Di Lorenzo ML, Knitter M, Longo A, Dobrzyński M, et al. Design, clinical applications and post-surgical assessment of bioresorbable 3D-printed craniofacial composite implants. Biomater Sci. 2024;12:3374–88.
23. Jeyaraj G. Transformative impact of 3D-Printed implants and virtual surgical planning in oral cancer reconstruction. Oral Oncol. 2024;156:106896.
24. Shu T, Wang X, Li M, et al. Nanoscaled titanium oxide layer provokes quick osseointegration on 3D-Printed dental implants: A domino effect induced by hydrophilic surface. ACS Nano. 2024;18(1):783–97.
25. Milano F, Dibart S, Montesani L, Guerra L. Computer-guided surgery using the piezocision technique. Int J Periodontics Restor Dent. 2014;34(4):523–9.
26. deGMdeP MA, VdenH JW, Baan F, Bruggink R, Bloemen M, B EM, O EM. Highly variable rate of orthodontic tooth movement measured by a novel 3D method correlates with gingival inflammation. Clin Oral Investig. 2021;25(4):1945–52.
27. Chen J, Ning R. Evaluation of root resorption in the lower incisors after orthodontic treatment of skeletal class III malocclusion by three-dimensional volumetric measurement with cone-beam computed tomography. Angle Orthod. 2023;93(3):320–7.
28. Charavet C, Lecloux G, Jackers N, Albert A, Lambert F. (2019) Piezocision-assisted orthodontic treatment using CAD/CAM customized orthodontic appliances: a randomized controlled trial in adults. European Journal of Orthodontics. First published on January 16, 2019. https://doi.org/10.1093/ejo/cjy082
29. Gibreal O, Hajeer MY, Brad B. Efficacy of piezocision-based flapless corticotomy in the orthodontic correction of severely crowded lower anterior teeth: a randomized controlled trial. Eur J Orthod. 2019;41:188–95.
30. Wang Y, Zhang H, Sun W, et al. Macrophages mediate corticotomy accelerated orthodontic tooth movement. Sci Rep. 2018;8(1):16788.
31. Apalimova A, Roselló, Jané-Salas E, et al. Corticotomy in orthodontic treatment. Syst Rev Heliyon. 2020;6(5):e04013.
32. Alqadasi B, Aldhorae K, Halboub E, Mahgoub N, Alnasri A, Assiry A, Xia HY. The effectiveness of Micro-osteoperforations during canine Retraction: A Three-dimensional randomized clinical trial. J Int Soc Prev Community Dent. 2019;9(6):637–45.
33. Alkebsi A, Al-Maaitah E, Al-Shorman H, Abu Alhaija E. Three-dimensional assessment of the effect of micro-osteoperforations on the rate of tooth movement during canine Retraction in adults with class II malocclusion: A randomized controlled clinical trial. Am J Orthod Dentofac Orthop. 2018;153(6):771–85.
34. Ciurla A, Szymańska J, Płachno BJ, Bogucka-Kocka A. Polymorphisms of encoding genes IL1RN and P2RX7 in apical root resorption in patients after orthodontic treatment. Int J Mol Sci 2021;22(2).
35. Kalra S, Gupta P, Tripathi T, Rai P. External apical root resorption in orthodontic patients: molecular and genetic basis. J Family Med Prim Care. 2020;9(8):3872–82.

36. Pizzo G, Licata ME, Guiglia R, Giuliana G. Root resorption and orthodontic treatment. Review of the literature. Minerva Stomatol. 2007;56(1–2):31–44.
37. Loi F, Córdova LA, Pajarinen J, et al. Inflamm Fract Bone Repair Bone. 2016;86:119–30.
38. Ji Y, Tang Y, Wu Q, Huang D, Zhu J, Kang F. The effects of mandibular osteotomy on maxillary orthodontic tooth movement and bone remodelling in a rat model. Eur J Orthod. 2021;43(4):467–472. https://doi.org/10.1093/ejo/cjaa053. PMID: 32929502.
39. Lorenzo J. Interactions between immune and bone cells: new insights with many remaining questions. J Clin Invest. 2000;106(6):749–52.
40. Wei S, Kitaura H, Zhou P, Ross FP, Teitelbaum SL. IL-1 mediates TNF-induced osteoclastogenesis. J Clin Invest. 2005;115:282–90.
41. Kindle L, Rothe L, Kriss M, Osdoby P, Collin-Osdoby P. Human microvascular endothelial cell activation by IL-1 and TNF-alpha stimulates the adhesion and transendothelial migration of Circulating human CD14 + monocytes that develop with RANKL into functional osteoclasts. J Bone Min Res. 2006;21:193–206.
42. Wu Q, Zhou XK, Huang DQ, et al. IL-6 enhances osteocyte-mediated osteoclastogenesis by promoting JAK2 and RANKL activity in vitro. Cell Physiol Biochem. 2017;41(4):1360–9.
43. Tang Y, Zhu J, Huang DQ, et al. Mandibular osteotomy-induced hypoxia enhances osteoclast activation and acid secretion by increasing Glycolysis. J Cell Physiol. 2019;234(7):11165–75.
44. Tang Y, Li XZ, Cai Y, et al. Hypoxia-induced factor 1α promotes osteotomy-induced regional acceleratory phenomenon via DC-STAMP mediated membrane fusion. Oral Dis. 2023;29(5):2139–53.

## Publisher's note