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A pilot study of mandibular expansion in combination with a fixed-appliance for increasing the effective space of the mandibular arch

Finite element analysis and three-dimensional cone-beam computed tomography

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Abstract

Techniques for enhancing the effective space of the mandibular arch are urgently needed. Therefore, this study aimed to perform mandibular expansion in combination with a fixed-appliance technique, with preliminary monitoring by finite element analysis and 3-dimensional cone-beam computed tomography (CBCT).

Finite element models were structured according to CBCT images of a 14-year-old girl. The von Mises stress of the alveolar bone and tooth displacement were assessed in different models. The technique was also applied in an 11-year-old boy. CBCT was performed at post-expansion, post-retention, post-treatment and 2 years after treatment. Tooth movement and alveolar bone stress were assessed by the CAD software.

Finite element analysis suggested that the teeth tended to stand upright in the buccal side in the expander model compared with the expander-remove model. However, minimum tooth change was observed in the normal model, indicating highest stability. The von Mises stress of the alveolar bone was decreased in the normal model compared with the expander model, suggesting that buccal-inclined teeth could more easily lead to alveolar bone stress than normal ones. Based on CBCT data and the 3D mandibular dentition model fitting, mandibular teeth tended to be upright in the buccal side after retention compared with the post-expansion condition, which somewhat differed from finite element analysis results. Furthermore, dehiscence and fenestration were not observed.

This expansion technique is expected to increase the effective space after mandibular expansion and reduce buccal alveolar bone stress.

Abbreviations: 3D = three-dimensional, CBCT = cone-beam computed tomography, FE = finite element.

Keywords: computer assisted three-dimensional imaging, expansion technique, finite element analysis, orthodontic tooth movement

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1. Introduction

With respect to transverse dimension, constricted arch problems have been solved through expansion, with increments in arch dimensions having been clearly demonstrated.[1,2] Mandibular expansion has not been recommended because the maxilla has a mid-palatal suture,[3] unlike the mandible.[4] A variety of methods such as the Schwarz and Bi-Helix appliances have been used, with limited dimension change and questionable expansion of the effective space primarily due to the inclination of teeth.[5–8] Inter-canine and inter-molar widths tend to decrease during the post-retention period.[9–11] Therefore, effective techniques for enhancing the effective space of the mandibular arch should be considered. We hypothesized that mandibular expansion in combination with fixed-appliance treatment could increase the effective space of the mandibular arch by allowing mandibular teeth to be upright in the buccal side compared with traditional methods, slowing lingual relapse of the teeth during the post-retention period. In this technique, expansion and a fixed appliance are applied synchronously, with a round wire used during mandibular expansion and a rectangular wire applied during the retention period. A possible mechanism is that a mandibular expander can cause the teeth to move in the buccal

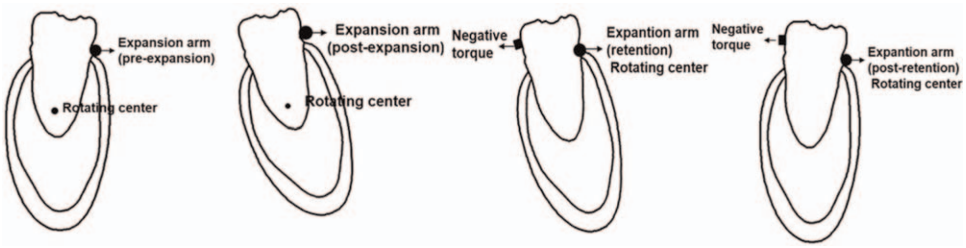

Figure 1. Possible mechanism of mandibular expansion in combination with a fixed-appliance technique (Braking-Force idea).

direction, a process which displaces the crown more than the root. Under this condition, the centre of rotation of the tooth is at the 1/3 of the root apex. When the NiTi-rectangular wire is applied as bracket after expansion combined with the expander as a retainer, the centre of rotation of the tooth locates at the dental cervix, allowing the teeth to be upright in the buccal side after retention, leading to a space-loss decrease during the post-retention period; thus, the expansion-derived effective space of the mandibular arch is increased (Fig. 1). This new method developed by our team was coined Braking-Force, since it allows root movement control. First, tooth tipping movement (buccal-lingual or mesial-distal direction) could be allowed. Then, the crown is braked, while the root is caused to move in the same direction as the crown using additional force. Finally, the tooth stands upright at the alveolar bone realizing the body movement. This could be used, not only for maxillary or mandibular expansion, but also probably for pushing molars to the distal direction, which is also a clinical challenge.

Three-dimensional (3D) finite element (FE) analysis is a contemporary research tool used for numerical simulation of the mechanical processes of a real physical system that offers several advantages, including accurate representation of complex geometries and simple model modification.[12] It is also considered a valid and reliable approach for quantitative evaluation of stress-strain in dentoalveolar structures.[13] Moreover, it provides the option to simulate orthodontic force systems applied clinically, thereby limiting the number of animal experiments. To test the hypothesis stated above, the present study was conducted with the aims to

1. evaluate the effects of mandibular expansion in combination with a fixed-appliance technique, which could allow the teeth to be upright in the buccal side after retention and
2. slow lingual relapse of the teeth during the post-retention period, using FE analysis and 3-dimensional cone-beam computed tomography.

2. Materials and methods

2.1. Research design

The mandibular FE model was constructed based on a cone-beam computed tomography (CBCT) scan of a 14-year-old girl in Chongqing Key Laboratory of Oral Diseases and Biomedical Sciences, Stomatological Hospital of Chongqing Medical University, Chongqing, China. Then, the model was applied to evaluate an 11-year-old boy complaining mainly of tooth crowding, who presented to the Department of Orthodontic Clinic, Air Force Medical Center, PLA, Beijing, China. The study protocol was approved by the ethics committee of Air Force Medical Center, PLA. Informed consent was obtained from the subject's parents prior to the study.

2.2. FE analysis

SolidWorks and ANSYS were applied to model FEs and mechanical analysis, respectively. SolidWorks, a leading, mainstream 3D CAD solution, is powerful, easy to learn and use, and technologically innovative. It provides various design plans, reduces errors in the design process, and improves product quality. ANSYS is a large-scale universal FE analysis (FEA) software developed by the American company ANSYS, which integrates fluid-structure, electric-magnetic and sound field analyses. It is widely applied in the field of biomedicine. Because ANSYS is powerful and easy to use, it has become the most popular FEA software worldwide.

For establishing a mandibular FE model, CBCT (slice thickness, 1 mm; pixel size, 0.42 mm) was performed in a 14-year-old girl. Using the CAD software (Dassault Systems Solid Works, USA), scaling and Boolean operations on the surface model of individual teeth were performed. The cortical bone, trabecular bone and periodontal ligament with average thicknesses of 2.0, 2.0, and 0.2 mm were produced, respectively. Five materials, including teeth, mucosa, trabecular bone, cortical bone, and periodontal ligament, were assembled in order to generate the geometric model. They were assumed to be linearly elastic, homogeneous and isotropic. Furthermore, the fixed expander, bracket, band and arch wire were designed and modelled with the CAD software (Dassault Systems Solid Works). NiTi-arch wires were used at the dimensions of $0.48 \times 0.64\,mm^2$ (0.019×0.025), 0.016 inch (the arch wires only being used for connection). The bracket had a 0.022-inch slot size. The teeth were tilted to the buccal side appropriately in the expansion models: incisors, 4°; canine teeth, 8°; first premolars, 10°; second premolars, 12°; first molars, 6°. The constructed geometric model was imported into the FE software ANSYS16.0 (Swanson Analysis Systems, USA). Adjacent FEs were connected by nodes. Table 1 provides the model types and numbers of elements and nodes. In addition, constraints were

Table 1

Numbers of elements and nodes.

Models	Elements	Nodes
Normal model (Model A)	288,103	531,921
Expander-remove model (Model B)	329,605	595,589
Expander model (Model C)	344,570	628,321
Normal $model_1$ (Model D)	288,103	531,921
Expander $model_1$ (Model E)	347,176	643,000

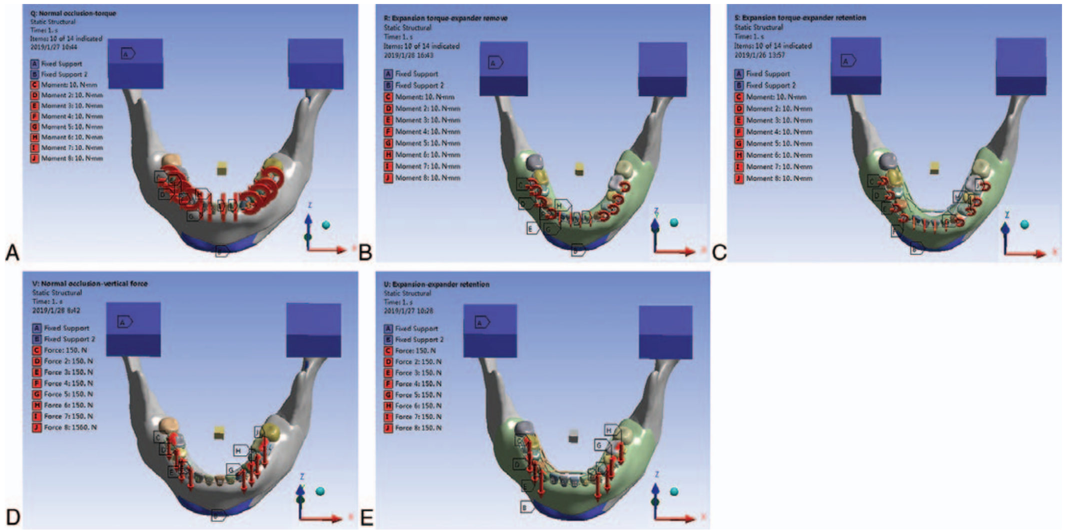

Figure 2. Simulated FE models. (A) Normal model (Model A); (B) Expander-remove model (Model B); (C) Expander model (Model C); (D) Normal model$_1$ (Model D); (E) Expander model$_1$ (Model E).

localized on the bilateral TMJ and mental region as a fixed boundary in all three axes. The 3D coordinates were: X, transverse direction; Y, antero-posterior direction; Z, vertical direction. Positive values indicate inward, backward, and upward displacements on the X, Y, and Z planes, respectively. FE models were included in the normal model (Model A-A, without mandibular expansion), expander-remove model (Model B-A, expander removed), expander model (Model C-A, expander preserved), normal model$_1$ (Model D-A, without mandibular expansion) and expander model$_1$ (Model E-A, expander preserved) (Fig. 2). The mechanical properties used for simulation are shown in Table 2.[14–18] Both side teeth were subjected to a 10 N/mm lingual torque on the brackets in Models A, B and C (Fig. 2). To simulate natural occlusal force, a static load of 150 N was applied once in the vertical direction in Models D and E (Fig. 2). The displacement of right teeth and the von Mises stress of the alveolar bone were observed.

Table 2

Physical properties of the materials.

Material	Poisson's ratio	Young's modulus (MPa)	Reference
Teeth	0.30	$20.7E^3$	[14]
Periodontal ligament	0.45	50	[15]
Trabecular bone	0.30	$9.7E^2$	[16]
Cortical bone	0.30	$10.7E^3$	[16]
Bracket, band, expander	0.30	$2\ E^5$	[17]
NiTi-arch wire	0.30	$6\ E^4$	[18]

2.3. CBCT data measurement

CBCT data of an 11-year-old boy in Air Force Medical Center, PLA were assessed. The patient was treated with mandibular expansion in combination with the fixed-appliance technique (Fig. 3). A Haas expander and fixed screw expander were used simultaneously. Imaging was obtained on a CBCT instrument (Galileo, Sirona Dental Systems, Germany). Patient information was recorded in the database, and the DICOM datasets (post-expansion-T_1) of the patient were imported into the program. The same imaging recording was performed after retention (T_2) for 6 months, post-treatment (T_3) and 2 years post-treatment (T_4).

Measurements were performed for cross-sectional images obtained at $T_{1–4}$. Two linear measurements were performed on mandibular sections, including the buccal cusp tip and root apex. Mandibular long axis measurement was performed between the long axis of the mesial root apex and the central fossa (Fig. 4).

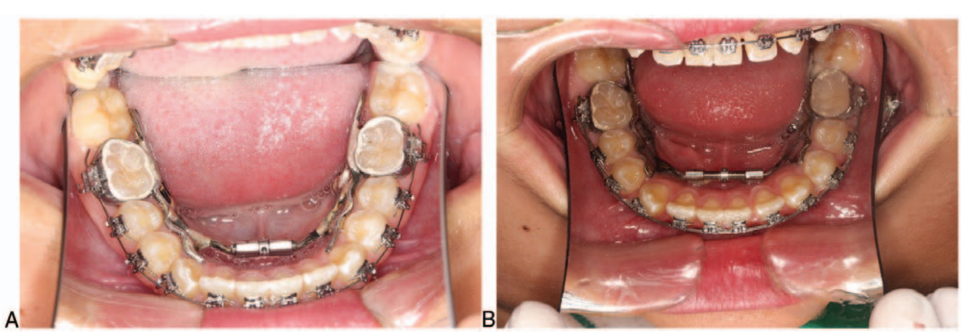

Figure 3. Mandibular expansion in combination with the lingual torque technique. (A) Mandibular expansion period (round wire application); (B) Mandibular retention period (rectangular wire application).

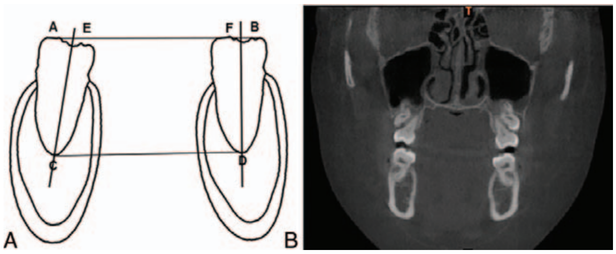

Figure 4. Mandibular linear measurements. (a) Sketched map of mandibular linear measurements: (AB) distance of the buccal cusp tip; (CD) distance of the root apex; (ECD) measurement of the left long axis; (FDC) measurement of the right long axis. (b) CBCT section of mandibular linear measurements.

The canine teeth were left out because of their position on the corner of the mandibular.

2.4. Mandibular 3D model fitting

The process of 3D model construction was identical to FE analysis. The 3D models of different treatment periods (T_1, T_2, T_3, and T_4) were constructed. Each 3D model of mandibular dentition was extracted from the mandible model and fitted.

3. Results

3.1. Findings of FE analysis

FEA results are shown in Figures 5 and 6. The displacement of the right teeth is illustrated in Figure 5. All crowns moved to the lingual side after applying the lingual torque. The root-apexes moved to the buccal side in Models A and C; however, some root-apexes (second premolars and molars) moved to the lingual side in Model B. The absolute crown displacement was more pronounced than that of the root-apex in all models. Crown displacement was lower in Model C than in Model B; the lowest displacement appeared in Model A. The displacement of the root-apex in Model C was highest among all models; the lowest displacement appeared in model A. The von Mises stress values of the alveolar bone for Models D and E are shown in Figure 6. The maximum von Mises stress of the alveolar bone for Model D was 38.212 Mp; Model E had 43.699 Mp. The minimum von Mises stress values of the alveolar bone for Models D and E were $4.924e^{-5}$ Mp and $9.0787e^{-5}$ Mp, respectively. The von Mises stress of the alveolar bone in Model D was lower than that observed for Model E.

3.2. CBCT data

The measured CBCT data are shown in Figure 7 and Table 3. Apart from mandibular first molar, the tooth crown moved to the lingual side throughout basing on the displacement data of the buccal cusp and root apex widths. The most pronounced change occurred from retention ending to post-treatment (Fig. 7A). Basically, no changes in linear measurements (inter-canine, inter-premolar, and intermolar buccal cusp widths) were found between post-retention and post-expansion. Slightly differences were observed between post-treatment and 2-year retention (Fig. 7A). The displacement of the root apex was increased from post-retention to post-expansion and from post-treatment to 2 years post-treatment (Fig. 7B). The absolute crown displacement was lower than that of the root-apex from post-expansion to post-retention, somewhat differing from the results of FE analysis (Table 3). Apart from mandibular first molar, the long axis of the teeth was decreased throughout basing on the long axis measurement data. The most pronounced change occurred from retention ending to post-treatment. From the completion of the

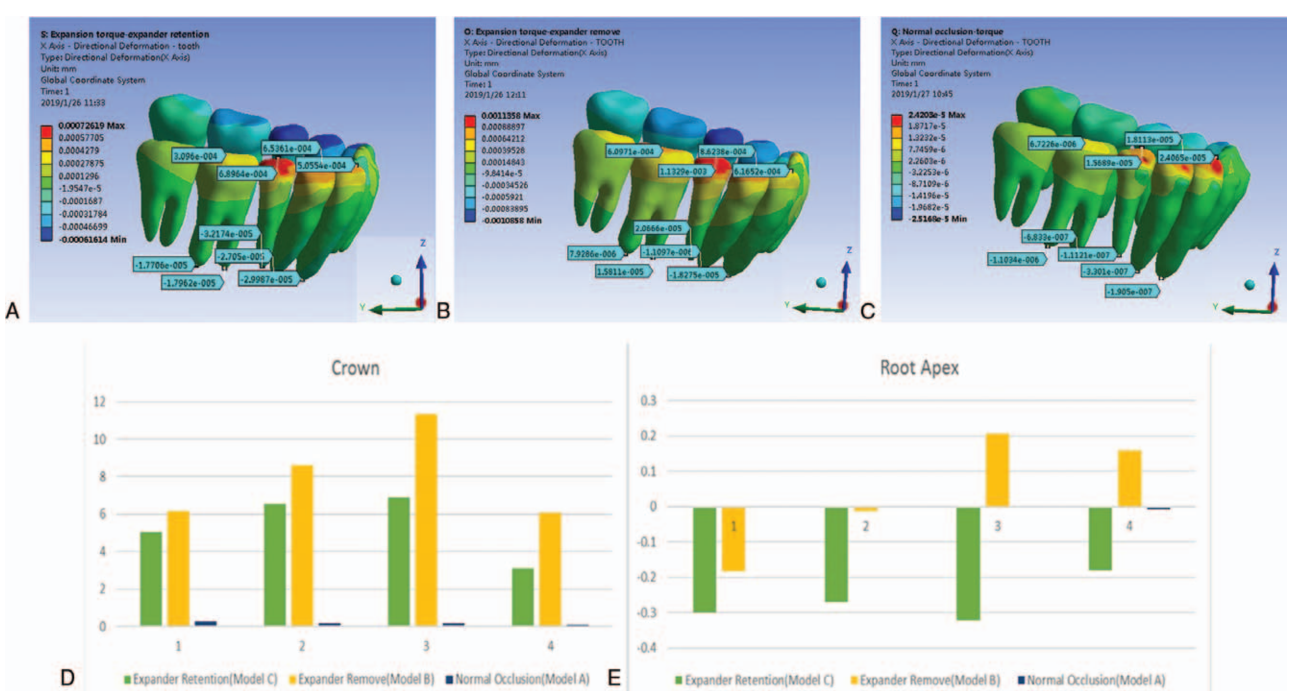

Figure 5. Displacement of right teeth (e-4 mm). (A) Expander model (Model C); (B) Expander-remove model (Model B); (C) Normal model (Model A).

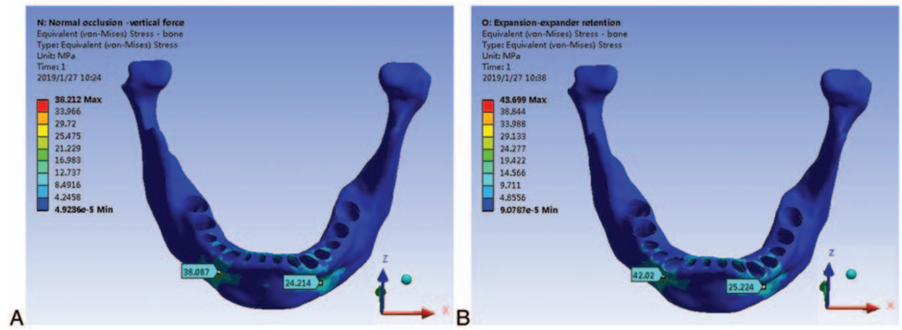

Figure 6. von Mises stress of alveolar bone. (A) Normal model$_1$ (Model D); (B) Expander model$_1$ (Model E).

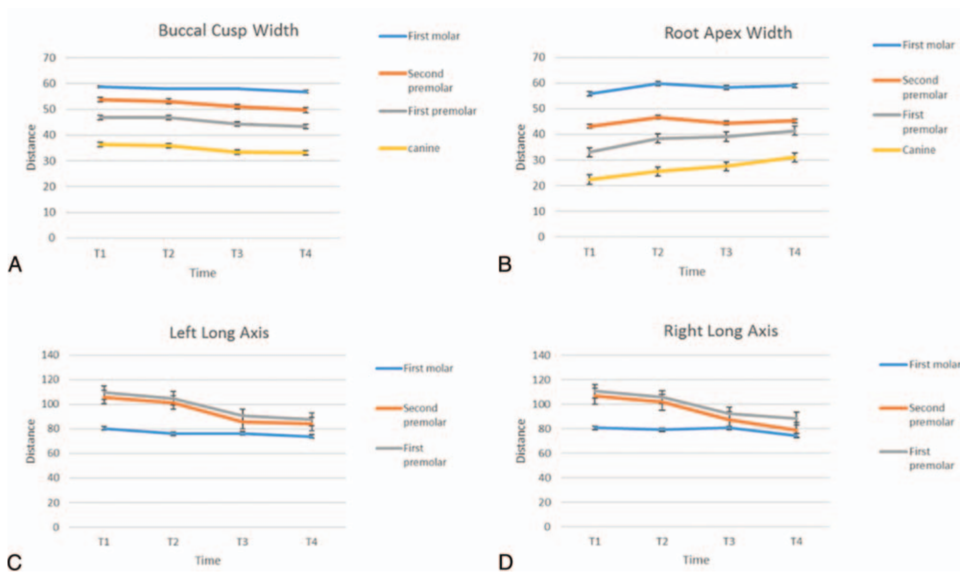

Figure 7. CBCT Data Measurement. (A) Buccal cusp width basically unchanged at post-retention vs post-expansion. A slight difference was observed between post-treatment and retention for 2 years. (B) Increase in root apex width at post-retention vs post-expansion and at post-treatment vs 2 years post-treatment (except second premolar); (C and D) the long axis of the teeth decreased throughout the study.

Table 3

CBCT measurement results.

Time	TP	BCT (AB)	RA (CD)	L A (left) (ECD)	L A (right) (BDC)
	6	58.81	55.78	80.39	80.7
T1	5	53.79	43.13	105.85	106.68
	4	46.73	33.06	109.49	110.64
	3	36.42	22.34		
	6	57.98	59.79	75.96	79.35
T2	5	53.12	46.62	101.32	101.75
	4	46.69	38.39	104.9	105.65
	3	35.9	25.5		
	6	57.88	58.35	76.43	80.68
T3	5	51.05	44.37	85.68	87.57
	4	44.27	39.13	90.56	92.34
	3	33.35	27.51		
	6	56.84	58.97	73.91	74.48
T4	5	49.7	45.26	83.94	78.92
	4	43.31	41.46	87.7	88.6
	3	33.04	31.01		

T1, post-expansion; T2, post-retention; T3, post-treatment; T4 2 years post-treatment; 3-4, first premolar; 5, second premolar; 6, first molar.
BCT = buccal cusp tip, LA = mandibular long axis, RA = root apex, TP = tooth position.

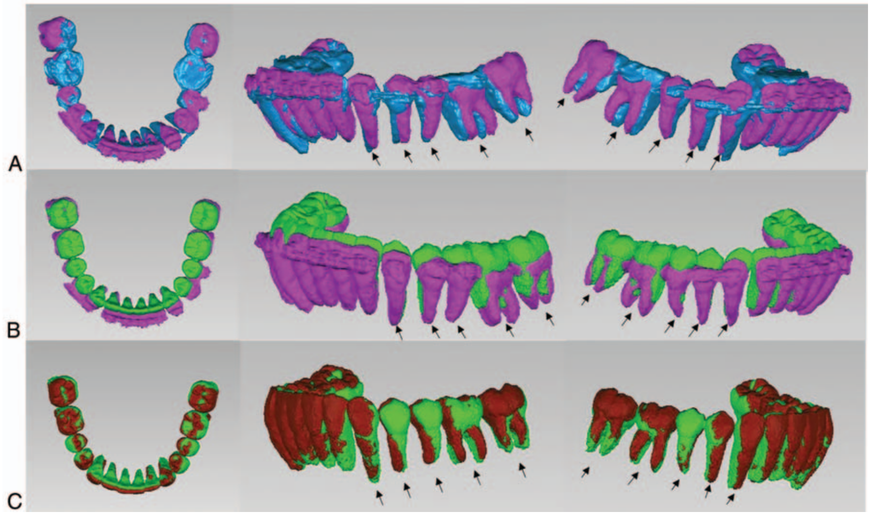

Figure 8. (A) Change in position of teeth at different stages. The root moved to the buccal side, while the crown was basically unchanged during the T_2–T_1 periods. (B) Both the root and crown moved to the lingual side during T_3–T_2. (C) Both root and crown were basically unchanged during T_4–T_3. The phenomenon of tooth crowding was not observed comparing post-treatment and 2 years post-treatment. Blue-T_1, post-expansion; Pink-T_2, post-retention; Green-T_3, post-treatment; Red-T_4, 2 years post-treatment.

mandibular expansion to the end of the therapy, we observed that the mandibular axis of mandibular molar inclined toward the cheek continually.

3.3. Mandibular 3D model fitting

Mandibular dentition 3D model fitting results at different treatment periods are presented in Figures 8–10. The root moved to the buccal side, while the crown was basically unchanged during the T_2–T_1 periods. As a result, mandibular teeth were found in the buccal side and tended to be upright compared with T_1 (Fig. 8A). Both the root and crown moved to the lingual side during the T_3–T_2 periods. As a result, the mandibular arch was reduced (Fig. 8B). Both root and crown were basically unchanged inT_4–T_3. The phenomenon of tooth crowding was not observed comparing post-treatment to 2 years post-treatment. As a result, the width of the mandibular arch was stable after retention for 2 years (Fig. 8C). Dehiscence and fenestration were not detected, even when the root profile was obviously altered, between post-retention and post-expansion (Fig. 9A–D). The width of the mandible was gradually increased from post-expansion to 2 years post-treatment (Fig. 10A–C).

4. Discussion

The newly developed technique could increase the effective space after mandibular expansion and reduce buccal alveolar bone stress. The reported level of expansion varied between the maxilla and mandible because of the difference in expansion mechanism. The effects of mandibular expansion are localized to alveolar bones and mainly induce tooth inclination.[5–8] As a result, the expansion space is easily relapsed. Therefore, enhancing the effective space by mandibular expansion is important for the treatment effect.

This study provides useful information regarding the effect of lingual torque during the retention period of mandibular expansion. Based on FEA results, the directions of crown displacement and the root-apex were opposite in Models B and C after lingual torque application, suggesting that the teeth tend to tip in the opposite direction taking the upright position. Furthermore, crown displacement was higher in Model B compared with Model C, and root-apex displacement was higher in Model C than in Model B, suggesting that the centre of rotation of the teeth shifted up; the teeth in Model C tended to be upright in the buccal side compared with those in Model B. The displacement of crown and root-apex was lowest in Model A,

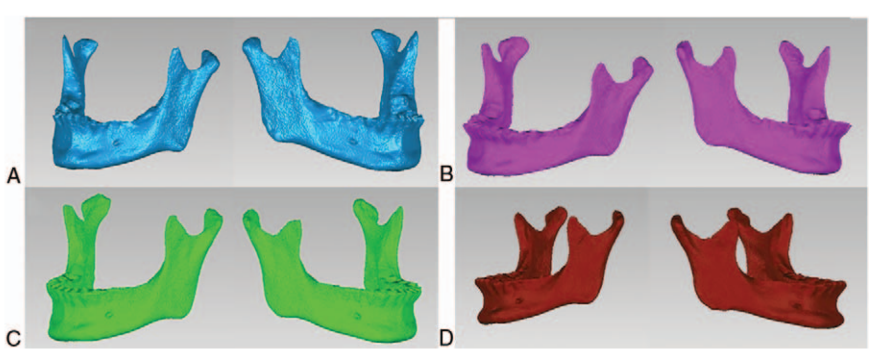

Figure 9. Mandibular bone models at different stages. (A) Post-expansion (Blue-T_1); (B) Post-retention (Pink-T_2); (C) Post-treatment (Green-T_3); (D) 2 years post-treatment (Red-T_4). Dehiscence and fenestration were not detected.

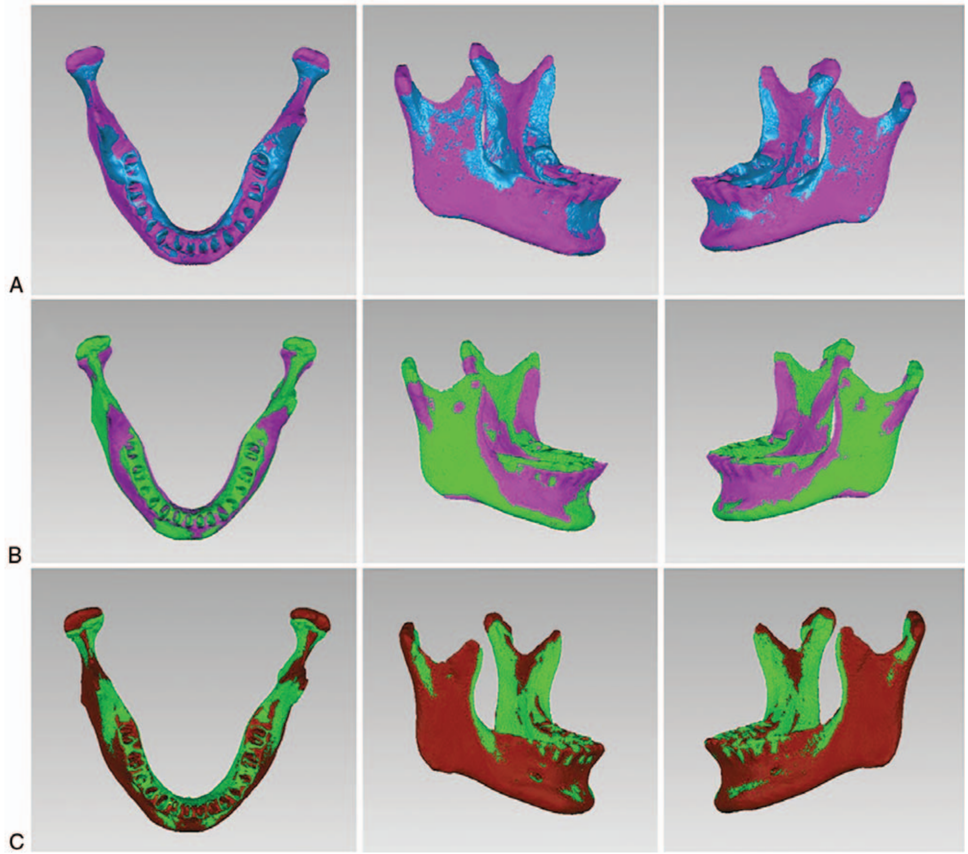

Figure 10. Comparisons of the mandibular bone at different stages. (A) Post-expansion vs post-retention. (B) Post-retention vs post-treatment; (C) Post-treatment vs 2 years post-treatment. The width of mandible was gradually increased from post-expansion to 2 years post-treatment. Blue-T_1, post-expansion; Pink-T_2, post-retention; Green-T_3, post-treatment; Red-T_4, 2 years post-treatment.

suggesting minimum change of the teeth in the normal model, indicating the teeth in the normal model were most stable. Therefore, the more the teeth are up-right, the less the space-loss decrease. The absolute displacement of the crown was higher than that of the root-apex in all models, suggesting that the centre of tooth rotation is at the root direction of the dental cervix and causes the teeth to be upright in the lingual side compared to post-expansion, in contrast to clinical application (3D mandibular dentition fitting) results. The possible reason is that FEA results depict the initial displacement and the expander had a slight deformation possibly at the beginning of torque application, leading to result deviation.

The stress associated with Model E was larger than for Model D, suggesting that the stress of the buccal alveolar bone would increase during the retention period due to tooth buccal inclination after applying the vertical force, a phenomenon which may increase the risk of alveolar bone resorption. Therefore, it is necessary to ensure that teeth have a tendency to stand upright in the alveolar bone as soon as possible in order to decrease the stress of the buccal alveolar bone. Based on FEA results, mandibular expansion in combination with a fixed-appliance technique could cause the teeth to tend to be upright during the retention period, a state which decreases the stress of the buccal alveolar bone. In addition, the von Mises stress of the alveolar bone was larger than the force that the bone could stand after applying the vertical force. However, buccal dehiscence and fenestration were not detected in the clinical application, perhaps because bone remodelling was not considered during the FEA in this study.[19]

Based on CBCT measurement data and the mandibular dentition model fitting, the teeth tended to be upright in the buccal side comparing post-retention with post-expansion, that is, the expansion space was easier to keep than post-expansion based on FE analysis results. During the 2-year follow-up period after the orthodontic therapy, the angle of the dental axis decreased. But there was no tooth crowding while the movement of the apex was greater than that of the crown. A possible cause is an increase in the width of the mandible. We speculate that this phenomenon is not a sign of instability, and in this case the erect axis of the tooth will actually help the stability of the dental arch. According to our model measuring, the mandibular axis of mandibular first molar inclining continuously toward the cheek between the completion of the mandibular expansion and the end of the therapy. This may be related to the insufficient upright stability of the first molar during the expansion. The body of the screw rested back of the anterior teeth where the points of application were located. So the tail end of the expander were more flexible than the front end, making the insufficient upright stability of the molars. The arch wire were supposed to keep the first molar upright in order to obtain balanced occlusion after removal of expander.

Our patient furthermore reported no buccal dehiscence and fenestration after retention, although the root profile was more obviously changed after retention. This may be related to this technique, which possibly leads to the teeth tending to be upright during the period of retention, a timepoint which is earlier than found for traditional expansion methods.[20–22] As a result, the stress caused by teeth buccal inclination was relieved as soon as possible; consequently, the risk of dehiscence and fenestration was reduced, a state verified by FEA results. Another possible reason is that the patient was in the prepubertal stage (Fig. 10A–C), in which alveolar bone remodelling is faster than in adults. The root profile was more obviously altered, based on mandibular 3D model results comparing post-retention and post-expansion. A possible explanation for this observation is that mandibular expansion leads to tooth buccal bodily movement; however, alveolar bone remodelling is slower than tooth movement, and requires a long time for reconstruction.[23]

The main problem solved in this study is that teeth can only be aslant moved after mandibular arch expansion. After arch expansion, the teeth were inclined to the buccal side. During the subsequent treatment, the teeth would tilt toward the lingual side. So, the arch expansion gap was difficult to maintain.[5–8] In this study, the concept of braking force was proposed. First, the teeth were moved towards the buccal side by the expansion device, which was similar to the effect of previous expansion devices. Then, we used the expansion arm to brake the dental crown and bring the square wire to the labial side (this was equivalent to adding a torque on the cheek side to the labial side; since the dental crown was braked, the root was moved to the buccal side and finally achieved the overall movement of the tooth). The results of the first three FE models in the work showed that the erect teeth were most stable. The braking force caused the teeth to tend to erect in the alveolar bone, which is more favorable than the traditional method for maintaining effective clearance after arch expansion. In this way, non-extraction treatment can be selected for extraction/non-extraction cases with the straight-type arch stenosis, thus reducing the facial shape change caused by tooth extraction as well as the risk of old face occurrence,[24] even for cases of surgical/non-surgical arch expansion margin, non-surgical treatment can be selected to alleviate the patient's pain and reduce possible complications from surgery.[25–27] This was also the reason why the teeth should stand upright in the alveolar bone, and the current method was developed to hold the teeth upright on the buccal side of the original teeth, thus effectively maintaining the expansion gap and tooth stability. Meanwhile, placing the teeth upright as early as possible could reduce the risk of trauma, and these results were confirmed by the latter two FE models. We also applied mandibular arch expansion combined with the fixed orthodontic technique derived from the theory of braking force to clinical cases. After 2 years of observation, good results were obtained without recurrence. The width of the arch remained stable. Taken together, these findings demonstrated that the concept of braking force is feasible, and the effect of mandibular arch expansion combined with the derived fixed orthodontic technique is positive. This technique could also be applied to maxillary arch expansion, which deserves further investigation.

The limitations of this study should be mentioned. First, FEA is a mathematical analysis method that does not necessarily fully simulate the clinical situation. However, the modeling method used in this study was rigorous, and application objects were matched. Therefore, although biomechanical values may not be completely accurate in quantity, the model quality is satisfactory. Secondly, the biomechanical results involved in this study were not validated in a large number of patients undergoing treatment. Therefore, further combined studies of FE analysis, experimental studies and long-term clinical evaluation are needed to confirm the present findings.

5. Conclusions

Mandibular expansion in combination with a fixed-appliance technique may be a promising method for increasing the effective space by mandibular expansion, reducing the stress of the buccal alveolar bone. This new technique deserves further investigation.

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References

[1] Garrett BJ, Caruso JM, Rungcharassaeng K, et al. Skeletal effects to the maxilla after rapid maxillary expansion assessed with cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2008;134:8–9.
[2] Handelman CS. Adult nonsurgical maxillary and concurrent mandibular expansion treatment of maxillary transverse deficiency and bidental arch constriction. Semin Orthod 2012;18:134–51.
[3] Bruder C, Ortolani CLF, Lima TA, et al. Evaluation of palate area before and after rapid maxillary expansion, using cone-beam computed tomography. Dental Press J Orthod 2019;24:40–5.
[4] Sandstrom RA, Klapper L, Papaconstantinou S. Expansion of the lower arch concurrent with rapid maxillary expansion. Am J Orthod Dentofacial Orthop 1988;94:296–302.
[5] Tai K, Park JH, Mishima K, et al. 3-Dimensional cone-beam computed tomography analysis of transverse changes with Schwarz appliances on both jaws. Angle Orthod 2011;81:670–7.
[6] Housley JA, Nanda RS, Currier GF, et al. Stability of transverse expansion in the mandibular arch. Am J Orthod Dentofacial Orthop 2003;124:288–93.
[7] Buschang PH. Maxillomandibular expansion: short-term relapse potential and long-term stability. Am J Orthod Dentofacial Orthop 2006;129(4 suppl): S75–79.
[8] Ferris T, Alexander RG, Boley J, et al. Long-term stability of combined rapid palatal expansion-lip bumper therapy followed by full fixed appliances. Am J Orthod Dentofacial Orthop 2005;128:310–25.
[9] Little RM, Riedel RA, Stein A. Mandibular arch length increase during the mixed dentition: postretention evaluation of stability and relapse. Am J Orthod Dentofacial Orthop 1990;97:393–404.
[10] Vargo J, Buschang PH, Boley JC, et al. Treatment effects and short-term relapse of maxillomandibular expansion during the early to mid mixed dentition. Am J Orthod Dentofacial Orthop 2007;131:456–63.
[11] Shapiro PA. Mandibular dental arch form and dimension. Treatment and postretention changes. Am J Orthod 1974;66:58–70.
[12] Meijer HJ, Starmans FJ, Steen WH, et al. Loading conditions of endosseous implants in an edentulous human mandible: a three-dimensional, finite-element study. J Oral Rehabil 1996;23:757–63.
[13] Yang C, Wang C, Deng F, et al. Biomechanical effects of corticotomy approaches on dentoalveolar structures during canine retraction: a 3-dimensional finite element analysis. Am J Orthod Dentofacial Orthop 2015;148:457–65.

[14] Gardner SD, Chaconas SJ. Posttreatment and postretention changes following orthodontic therapy. Angle Orthod 1976;46:151–61.

[15] Little RM, Riedel RA, Artun J. An evaluation of changes in mandibular anterior alignment from 10 to 20 years postretention. Am J Orthod Dentofacial Orthop 1988;93:423–8.

[16] Shellhart WC, Moawad MI, Matheny J, et al. A prospective study of lip adaptation during six months of simulated mandibular dental arch expansion. Angle Orthod 1997;67:47–54.

[17] Buyuk SK, Guler MS, Bekci ML. Effect of arch wire size on orthodontic reverse closing loop and retraction force in canine tooth distalization: three-dimensional finite element analysis. J Orofac Orthop 2019;80:17–24.

[18] Razali MF, Mahmud AS, Mokhtar N. Force delivery of NiTi orthodontic arch wire at different magnitude of deflections and temperatures: a finite element study. J Mech Behav Biomed Mater 2018;77:234–41.

[19] Ajmera DH, Singh P, Wang C, et al. Analysis of dentoalveolar structures with novel corticotomy-facilitated mandibular expansion: a 3-dimensional finite element study. Am J Orthod Dentofacial Orthop 2017;151:767–78.

[20] Maki K, Sorada Y, Ansai T, et al. Expansion of the mandibular arch in children during the mixed dentition period–a clinical study. J Clin Pediatr Dent 2006;30:329–32.

[21] Tai K, Hotokezaka H, Park JH, et al. Preliminary cone-beam computed tomography study evaluating dental and skeletal changes after treatment with a mandibular Schwarz appliance. Am J Orthod Dentofacial Orthop 2010;138: 3.262.e261–262.e211; discussion 262–263.

[22] Motoyoshi M, Shirai S, Yano S, et al. Permissible limit for mandibular expansion. Eur J Orthod 2005;27:115–20.

[23] Wang YL, Wang TJ, Liu ZH. Changes in root and alveolar bone before and after treatment by retracting the upper incisors. Hua Xi Kou Qiang Yi Xue Za Zhi 2018;36:638–45.

[24] Cheng HC, Wang YC. Effect of nonextraction and extraction orthodontic treatments on smile esthetics for different malocclusions. Am J Orthod Dentofacial Orthop 2018;153:81–6.

[25] Sakamoto T, Hayakawa K, Ishii T, et al. Bilateral scissor bite treated by rapid mandibular expansion following corticotomy. Bull Tokyo Dent Coll 2016;57:269–80.

[26] Sahin T, Garreau E, Komakli Y, et al. Mandibular anterior segmental subapical osteotomy for incisor axis correction. J Stomatol Oral Maxillofac Surg 2017;118:271–8.

[27] Neto TJL, Maranhao CAA, Neto PJO. Pseudoaneurysm of facial artery after orthognathic surgery. J Craniofac Surg 2019;30:e607–9.