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Evaluation of root and alveolar bone development of unilateral osseous impacted immature maxillary central incisors after the closed-eruption technique

Xiangru Shi,[a] Xiaoyan Xie,[b] Junkang Quan,[c] Xiaozhe Wang,[c] Xiangyu Sun,[c] Chenying Zhang,[c] and Shuguo Zheng[d]
Beijing, China

Introduction: In this study, we evaluated root and alveolar bone development in unilateral osseous impacted immature maxillary central incisors by cone-beam computed tomography before and after closed-eruption treatment, in comparison with naturally erupted contralateral immature maxillary central incisors. **Methods and Results:** The study included 30 patients, 20 boys and 10 girls, with a mean age of 8.44 ± 1.20 years (range, 6.5-11.2 years). After treatment, the root lengths of both the impacted maxillary central incisors (10.66 ± 2.10 mm) and the contralateral maxillary central incisors (11.04 ± 1.76 mm) were significantly greater than their pretreatment values (6.67 ± 1.94 and 9.02 ± 2.13 mm, respectively). The root canal widths of the incisors decreased significantly after treatment. From the posttreatment cone-beam computed tomography images, the ratio of exposed root length to total root length and the thickness of the alveolar bone at 1 mm under the alveolar crest and at the apex were calculated to evaluate alveolar bone development. Impacted immature maxillary central incisors differed significantly from contralateral immature maxillary central incisors in labial exposed root length, labial ratio to total root length, and lingual alveolar crest. Clinical crown height was higher (statistically but not clinically) for the impacted incisors (9.87 mm) than for the contralateral incisors (9.37 mm). **Conclusions:** Impacted immature incisors grew to the same stage as did erupted contralateral incisors after closed-eruption treatment. Both incisor types had some alveolar bone loss, and thin alveolar bone surrounded the roots. (Am J Orthod Dentofacial Orthop 2015;148:587-98)

The maxillary central incisors are the most prominent teeth in the mouth, significantly affecting a child's facial appearance, esthetics, pronunciation, mastication, and psychology. Although the canine is the most frequently impacted tooth in the anterior region (incidence, 1%-3%[1]), an impacted maxillary central incisor is the most conspicuous to parents.

Many studies have demonstrated that the closed-eruption technique is an effective method of treating impacted teeth.[2-5] A strong positive relationship has been found between the necessary duration of this treatment and the patient's age,[1] and many researchers have reported that treatment begun in younger patients yields better results.[6]

However, much of this research into the closed-eruption technique showed important problems that need to be solved. The patients selected in most studies included children, adolescents, and even adults.[1,2,7] The root development of the impacted teeth was unclear. Most researchers studied only posttreatment examinations, with no comparison of pretreatment and posttreatment records. In most cases, the radiologic records used were periapical, panoramic, and cephalometric radiographs, which are not as accurate as cone-beam computed tomography (CBCT),

From the Peking University School and Hospital of Stomatology, Beijing, China.
[a]Postgraduate student, Department of Preventive Dentistry.
[b]Resident, Department of Oral and Maxillofacial Radiology.
[c]Resident, Department of Preventive Dentistry.
[d]Professor, Department of Preventive Dentistry.
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Address correspondence to: Shuguo Zheng, Department of Preventive Dentistry, Peking University School and Hospital of Stomatology, 22 Zhongguancun Avenue South, Haidian District, Beijing 100081, PR China; e-mail, zhengsg86@gmail.com.
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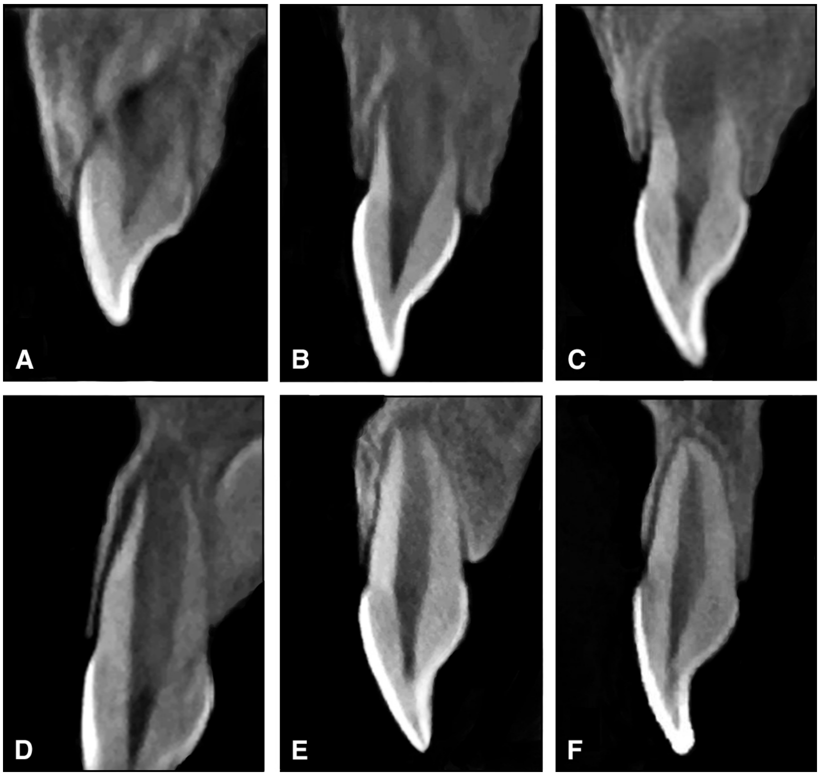

Fig 1. The stages of root development are classified as **A,** one quarter root formation; **B,** one half root formation; **C,** three quarters root formation; **D,** full root formation, open apex; **E,** full root formation, half-closed apex; and **F,** full root formation, apex closed.[8]

especially on rotated and dilacerated teeth. In many patients, it was found that the impacted tooth roots were rotated before the treatment, and the roots of most impacted teeth were dilacerated. Thus, a convincing evaluation of the treatment efficacy was not possible.

The aim of our study was to evaluate the root and alveolar bone development of unilateral osseous impacted immature maxillary central incisors by CBCT before and after early closed-eruption technique. Naturally erupted contralateral immature maxillary central incisors were used for comparison.

MATERIAL AND METHODS

A total of 244 patients with impacted maxillary central incisors were consecutively treated by one operator (S.Z.) in the Departments of Pediatric and Preventive Dentistry at the Peking University School and Hospital of Stomatology. Of these, 30 patients (20 boys, 10 girls) were included in our study. These patients met the following criteria: (1) the coexistence of a unilateral osseous impacted maxillary central incisor, whose root was in stages 1 to 5 (Fig 1)[8] at the beginning of the closed-eruption treatment, with a contralateral maxillary central incisor (control) that had already erupted but had not necessarily reached the occlusal plane; (2) the closed-eruption treatment had been finished for about 1 to 3 years; (3) complete diagnostic and treatment notes were available; (4) pretreatment and posttreatment CBCT records were available; (5) there was no mechanical obstacle to eruption: eg, supernumerary teeth, tumors, odontoma, or cysts; (6) the patient had no systemic disease; and (7) the patient and parents cooperated with the treatment plan and provided informed consent. The exclusion criterion was an injury to the maxillary frontal area before our study finished.

A diagnosis of impaction was evaluated clinically and radiologically when one immature maxillary central incisor was absent from the dental arch after the expected eruption time and the contralateral incisor had erupted at least 6 months earlier, or the eruption orientation of one central incisor was not toward the center of the alveolar ridge (confirmed by radiologic examination).

For the closed-eruption technique, a medical history was taken, and clinical and radiologic examinations (including CBCT) were conducted by a pediatric dentist

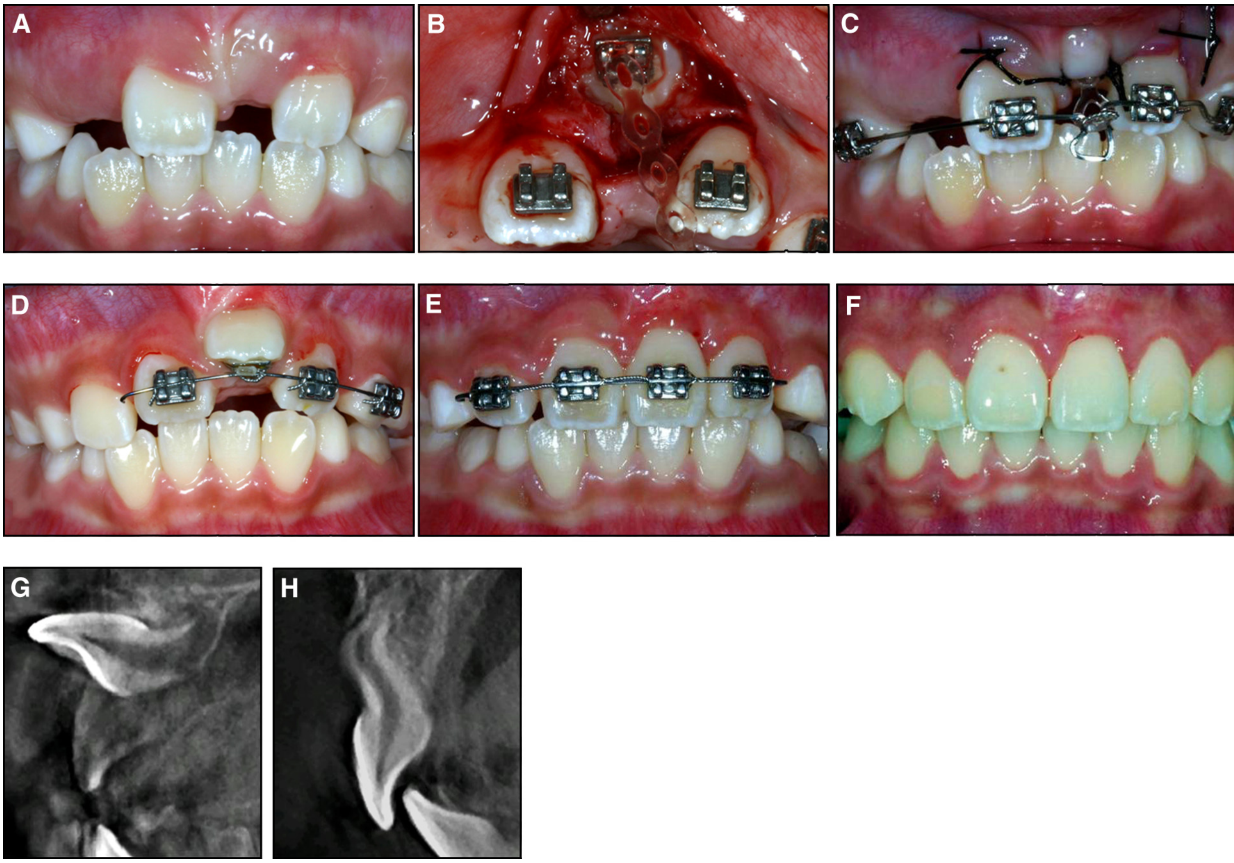

Fig 2. The patient was a girl, aged 6 years 10 months, with a unilateral osseous impacted immature maxillary central incisor: **A,** pretreatment view; **B,** surgical crown exposure showing the palatal surface; **C,** immediately postsurgical view; **D,** crown exposure caused by orthodontic traction force; **E,** the erupting incisor was properly aligned in the dental arch after 12.5 months of treatment, and the retention period started; **F,** final clinical aspect 1 year 10 months after the closed-eruption treatment; **G,** pretreatment CBCT; **H,** CBCT after the retention period.

[F2-4/C] (S.Z.) (Fig 2, *A* and *G*). Impacted immature maxillary central incisors were treated by this same dentist with a combined surgical-orthodontic technique. The impacted incisors were exposed with a full-thickness mucoperiosteal flap, and a bracket was bonded to the teeth during surgery. This was tied to an orthodontic elastomeric chain (Clear Generation II power chain, closed space 639-0002; Ormco, Orange, Calif) for orthodontic traction. A 0.016 × 0.022-in rectangular stainless steel archwire was used to obtain adequate anchorage, with an omega-shaped bend applied to enhance the retention of the elastomeric chain between the bracket and the wire. The elastomeric chain was at its original length. The flap was then repositioned over the incision and sutured. The sutures were removed on postoperative day 7 (Fig 2, *B* and *C*).

We cut off part of the elastomeric chain and reconnected it to the archwire to obtain 100 g of orthodontic traction force, measured with a testing machine (model 5969; Instron, Norwood, Mass), every 4 to 5 weeks. When the surface of the impacted incisor was exposed, a new bracket was bonded, and a 0.012-in round nickel-titanium archwire was used to guide the impacted central incisor toward the center of the alveolar ridge (Fig 2, *D*). There were 19 patients who had insufficient space to accommodate the impacted incisors before treatment. Two had only 5.5 mm of space and needed orthodontic expansion before treatment of the impacted tooth, whereas in the other 17 patients the midline of their maxillary incisors declined for 1 to 2 mm; this could be corrected during traction of the impacted incisors. Thus, the patients could receive treatment without delay. When the extruded incisor was aligned in the dental arch, the 0.012-in round archwire would be replaced by a 0.016 × 0.022-in rectangular nickel-titanium archwire if the axis of the extruded incisor

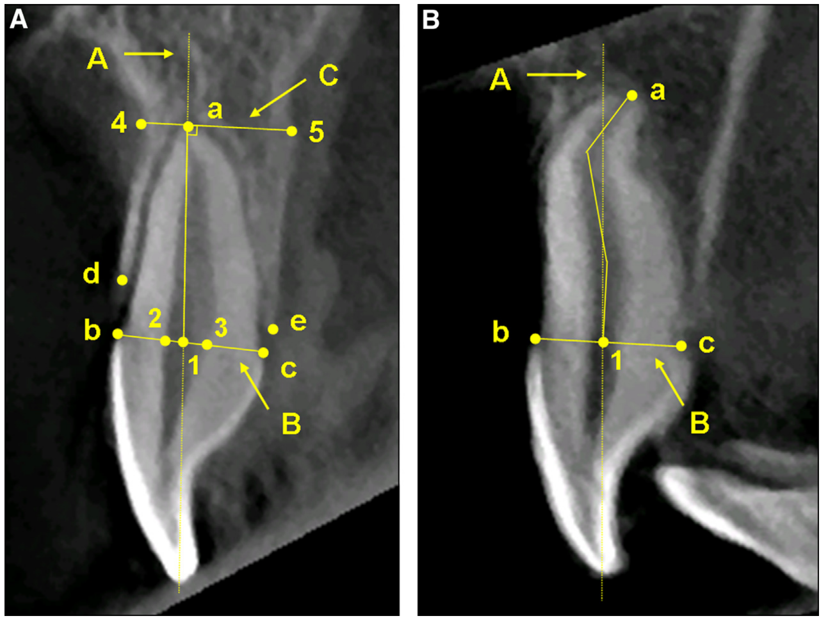

Fig 3. Illustration of reference points and lines used in this study. **A**: *a*, root apex; *b*, CEJ at the labial side; *c*, CEJ at the lingual side; *d*, alveolar crest at the labial side; *e*, alveolar crest at the lingual side; *A*, long axis of the central incisor; *B*, a line connecting *b* and c; *C*, a line connecting *4* and *5*; *1*, the point of intersection of lines *A* and *B*; *2*, the point of intersection of line *B* and the labial wall of the root canal; *3*, the point of intersection of line *B* and the lingual wall of the root canal; *4*, the point of intersection of a line perpendicular to the long axis of the incisor, with the labial contour of the maxilla; *5*, the point of intersection of a line perpendicular to the long axis of the incisor, with the lingual contour of the maxilla. **B**: When the root was dilacerated, root length was measured from point *1* to *a* in a line following the curvature, and the image would be rotated when needed.

was inclined. When the impacted incisor was brought into good alignment with the adjacent teeth, the closed eruption was considered complete.

The retention period began when a 0.016 × 0.022-in rectangular stainless steel archwire was placed in the labial brackets of the central and lateral incisors (Fig 2, *E*) as a fixed retaining appliance, without orthodontic force. Root and alveolar bone development was evaluated every 3 months by x-rays (periapical films).

Posttreatment CBCT images were obtained a minimum of 12 months later. If the retention period lasted more than 12 months, posttreatment CBCT was used after debonding; otherwise, CBCT images were taken at 12 months after the end of the treatment period (Fig 2, *F* and *H*).

Patient charts were reviewed for the following information: age, sex, medical history, bonding date, surgical exposure date, debonding date, and posttreatment CBCT examination date. The duration of the orthodontic traction time was calculated as the time between the application of the power chain and good alignment of the impacted incisor in the dental arch. The duration of the retention time was calculated as the time between the alignment of the impacted incisor in the dental arch and the debonding date of the maxillary central incisors. The duration of the follow-up time was calculated as the time between the debonding date of the maxillary central incisors and the posttreatment CBCT examination date. The total duration of the retention time and the follow-up time should be longer than 12 months.

In our study, 60 CBCT records of the 30 patients were collected using a 3-dimensional (3D) x-ray computed tomography device (MCT-1; J. Morita, Osaka, Japan). A voxel size of 0.125 × 0.125 × 0.125 mm was used for all subjects, and depending on the location of the impacted incisor, the other settings were as follows: cylindrical volumes of 4 × 4 cm to 6 × 6 cm, voltage of 80 kV, and current of 5 mA. The slice thickness was set at 1 mm, and the images were reformatted using the i-Dixel software package (version 1.27; J. Morita). On each CBCT record, an author (S.Z.) determined the root development stage of both maxillary central incisors. The measurements used in this study were modified from the reports of Kim et al[9] and Zhong et al.[10] Our reference points, lines, and measurement variables are [F3-4/C]
described in Figure 3 and Table 1.

Table I. Definitions of measurements used in this study (see Fig 3)

Measurement variable	*Definition*
RL	Root length: distance from a to 1
RCW	Root canal width: distance from 2 to 3
CEJW	CEJ width: distance from b to c
LaBL	Alveolar bone loss of labial side: distance from b to d measured parallel to line A
LiBL	Alveolar bone loss of lingual side: distance from c to e measured parallel to line A
LaCBT	Alveolar bone thickness of labial alveolar crest: thickness of the alveolar bone 1 mm under point d measured perpendicular to line A
LiCBT	Alveolar bone thickness of lingual alveolar crest: thickness of the alveolar bone 1 mm under point e measured perpendicular to line A
LaABT	Labial alveolar bone thickness at the root apex: distance from a to 4 measured perpendicular to line A
LiABT	Lingual alveolar bone thickness at the root apex: distance from a to 5 measured perpendicular to line A
%LaBL	Percentage of LaBL to RL
%LiBL	Percentage of LiBL to RL
%ABT	Percentage of alveolar bone thickness at the root apex to the CEJ width: LaABT + LiABT/CEJW

The labial and lingual cementoenamel junction (CEJ) and alveolar crest (the most coronal level of the alveolar bone) were defined on the median sagittal section of the crown, and the apical point was defined as the root apex on a 3D image. Root length was measured from the root apex to the intersection of the long axis of the incisor with the line connecting the labial and lingual CEJ. Alveolar bone loss was calculated from the CEJ to the alveolar crest on the 3D image. If the root was dilacerated, root length and alveolar bone loss were measured in a line following the curvature (the image was rotated as needed). Measurement of the root canal width was made between the intersections of the root canal wall and the line connecting the labial and lingual CEJ. Alveolar bone thickness at the alveolar crest was defined as the thickness of the alveolar bone 1 mm under the alveolar crest, measured perpendicular to the long axis of the incisor on the median sagittal section of the crown. Alveolar bone thickness at the root apex was measured from the root apex to the limit of the alveolar cortex, perpendicular to the long axis of the incisor.

Many previous studies have found that the adjacent permanent teeth used for anchorage can be affected by orthodontic traction.[11-13] To evaluate changes to the alveolar bone surrounding the anchorage incisors, we used CBCT records to assess pretreatment and posttreatment alveolar bone development for 25 contralateral maxillary central incisors that had reached the occlusal plane before treatment.

All measurements were repeated by 2 investigators (X.S., J.Q.) on 2 separate occasions at 1-week intervals; the average of the 2 measurements yielded the final result. During the follow-up examination when the posttreatment CBCT was taken, the crown heights of the incisors were also measured clinically from the midpoint of the incisal edge to the gingival margin on a line parallel to the long axis of the incisors.

Statistical analysis

For the metric variables, the results are expressed as medians, and means and standard deviations; for nominal variables, they are expressed as frequencies and percentages. The groups were compared using a paired *t* test or a Wilcoxon signed rank test, as indicated. Statistical analyses were carried out using the SPSS software package (version 17.0; SPSS, Chicago, Ill). All *P* values are 2-tailed, and the threshold for statistical significance was set at <0.05. The interclass correlation coefficient was 0.99.

RESULTS

Table II gives the mean patient ages at the time of surgery, the sex distribution, the location of impaction, the number of patients with root dilacerations, and the mean durations of closed-eruption treatment, retention, and follow-up. The study sample consisted of 30 patients, 20 boys and 10 girls, with a mean age of 8.44 ± 1.20 years (range, 6.5-11.2 years). There was no statistically significant difference between the male and female subjects in any measurement. Fifteen patients had caries, 8 patients had trauma on their deciduous predecessors, and 7 patients lacked any abnormalities in their deciduous incisors. No patient complained of significant discomfort caused by the therapy.

All 30 impacted immature central incisors were successfully aligned in the dental arches. In 28 patients their root apices had completed development, and in the other 2 patients the apices were at the same stage as those of the contralateral incisors (Table III). Reactions

Table II. Patient characteristics (N = 30)

Characteristic	n	Mean (SD)	Range
Sex			
Male	20		
Female	10		
Age (y)		8.44 (1.20)	6.5-11.2
Location of impaction			
Right	16		
Left	14		
Root dilacerations	24		
Mean closed-eruption treatment time (mo)		10.16 (2.73)	6.1-14.9
Mean retention time (mo)		14.26 (6.07)	5.0-29.3*
Mean follow-up time (mo)		1.76 (3.41)†	0-15
Sum of mean retention and follow-up times (mo)		16.02 (4.81)	12-29.3

*One patient delayed recall time for 12 months, and 4 patients accepted other orthodontic treatments immediately after the closed-eruption treatment; †median.

Table III. Root development (N = 30)

	Impacted incisors (n)		Contralateral incisors (n)	
Stage	Pretreatment	Posttreatment	Pretreatment	Posttreatment
1	8	0	1	0
2	10	0	9	0
3	4	0	10	0
4	7	1	3	1
5	1	1	7	1
6	0	28	0	28

of the impacted incisors to cold stimuli were consistent with those of the contralateral incisors. There was no obvious radiographic sign of root resorption or periapical radiolucency. The alveolar bone crest contours of both the labial and lingual sides of the incisors were U-shaped, and no fenestration or dehiscence was found. The mean duration of the closed-eruption treatment (time between applying the power chain and achieving good alignment of the impacted incisor in the dental arch) was 10.16 ± 2.73 months (range, 6.1-14.9 months).

Table IV reports the mean values relating to root and alveolar bone development. Statistically significant differences between the pretreatment and posttreatment root length were found for the impacted incisors (P <0.001) and the contralateral incisors (P <0.001). The mean pretreatment root length of the impacted incisors was significantly different from that of the contralateral incisors (P <0.001), but the difference at posttreatment was not significant (P = 0.771). The root length ratio of the impacted and contralateral incisors increased after treatment (P <0.001; Fig 4).

The root canal widths of both impacted and contralateral incisors were significantly narrower after treatment, although the difference was small (P = 0.007 and P = 0.021, respectively). No significant difference was identified between the root canal widths of the impacted and contralateral incisors before or after treatment (P = 0.284 and P = 0.221, respectively).

At posttreatment, the labial length of the exposed root and the ratio of that to the total root length were increased significantly for the impacted incisors compared with the contralateral incisors (P <0.001 and P <0.001, respectively), but the increases in lingual length and ratio were not significant (P = 0.443 and P = 0.469, respectively). For both the impacted and contralateral incisors, labial length of the exposed root and the ratio of that to the total root length were greater than lingual alveolar bone loss and the percentage of lingual alveolar bone loss (P <0.001; Fig 5).

The labial bone thicknesses at the alveolar crest and apex of the impacted and contralateral incisors were thinner (P <0.001) after treatment than the corresponding lingual values, and the impacted incisors differed from the contralateral incisors with respect to bone thickness of the lingual alveolar crest (P = 0.042). Other values relating to bone thickness showed no significant differences between the impacted and the contralateral incisors. The alveolar bone thickness at the apex, expressed as a percentage of the CEJ width, was similar for the impacted and contralateral incisors at posttreatment (P = 0.325; Fig 5).

A statistically significant difference was observed in crown height, which was higher for the impacted incisors than for the contralateral incisors (P = 0.045), but the difference was not clinically significant.

Examining the 25 contralateral incisors, we found that alveolar bone loss on the lingual side and its percentage to root length showed significant changes after treatment (P = 0.008 and P = 0.015, respectively). No significant differences between pretreatment and posttreatment values were observed for alveolar bone loss on the labial side, its percentage to root length, or bone thickness. Comparing the labial and lingual sides of the contralateral incisors, we found that bone loss, percentage of bone loss, bone thickness at the alveolar crest, and alveolar bone thickness at the apex differed significantly, both before and after treatment (P <0.002; Table V; Fig 6).

Table VI provides the characteristics of the impacted incisors. The categories were modified from the report of Wang and Hu.[14] In most cases, the impacted incisors were labially inverted, located around the middle third of the contralateral incisors' roots, and exhibited no declination in the coronal section.

Table IV. Root and alveolar bone development (N = 30)

Measurement	Impacted incisors Mean (mm)	SD	Range	Contralateral incisors Mean (mm)	SD	Range	P
RL							
Pretreatment	6.67	1.94	2.47-9.99	9.02	2.13	2.72-12.76	<0.001*
Posttreatment	10.66	2.10	6.98-14.83	11.04	1.76	7.75-13.55	NS*
P	<0.001*			<0.001*			
RCW							
Pretreatment	2.25	0.52	1.40-3.60	2.11	0.46	1.47-3.32	NS†,‡
Posttreatment	1.97	0.35	1.33-2.60	1.89	0.32	1.37-2.47	NS‡
P	0.007†,‡			0.021†,‡			
LaBL	2.91	1.63	0.20-7.05	1.40	0.91	0.00-4.99	<0.001†,§
LiBL	0.93	1.00	0.00-4.00	0.77	0.68	0.00-2.96	NS†,§
P	<0.001†,§			<0.001†,§			
%LaBL	29.34	18.70	2.01-64.83	13.02	8.64	0.00-45.49	<0.001*,†
%LiBL	9.48	12.10	0.00-56.26	6.97	5.97	0.00-22.67	NS*,†
P	<0.001*,†			<0.001*,†			
LaCBT	0.73	0.19	0.33-1.12	0.73	0.19	0.38-1.00	NS†,‡
LiCBT	1.40	0.64	0.63-4.19	1.20	0.41	0.71-2.66	0.042†,‡
P	<0.001†,‡			<0.001†,‡			
LaABT	4.24	1.97	0.18-7.74	4.95	1.41	1.53-7.67	NS*
LiABT	7.17	2.01	1.37-11.10	6.94	1.32	4.56-10.53	NS*,†
P	<0.001*			<0.001*,†			
%ABT	185.34	28.79	110.11-260.31	192.62	26.04	141.36-247.62	NS*,†
Crown height	9.87	1.16	6.99-11.75	9.37	1.17	6.86-11.66	0.045‡

NS, No statistical difference between variables.
*Adjusted α <0.0167 by Bonferroni correction; †α <0.05; ‡Wilcoxon signed rank test; §adjusted α <0.025 by Bonferroni correction.

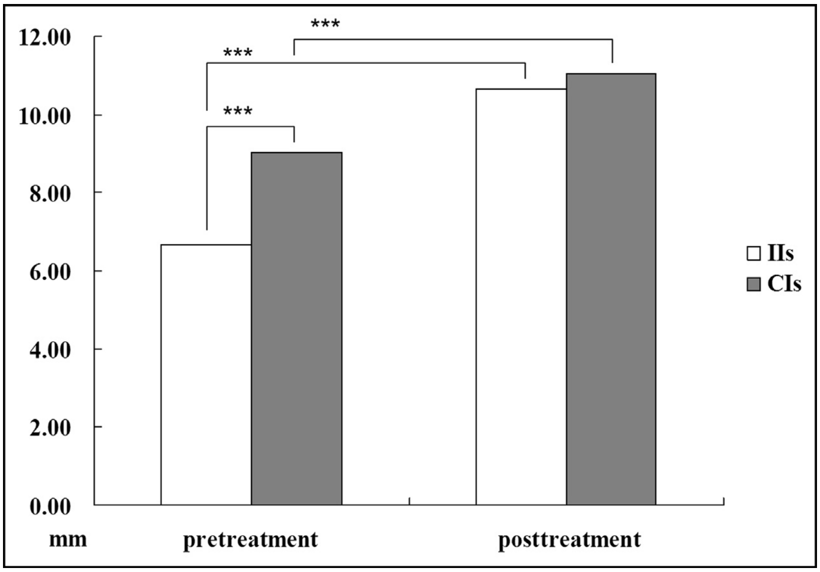

Fig 4. Root length of impacted incisors (*IIs*) and contralateral incisors (*CIs*) before and after treatment. ****P* <0.0167.

DISCUSSION

The roots of the 30 impacted incisors that we examined had not completed development when the treatment began. We found that their mean root length was shorter than that of the contralateral incisors, indicating that development was delayed in the impacted

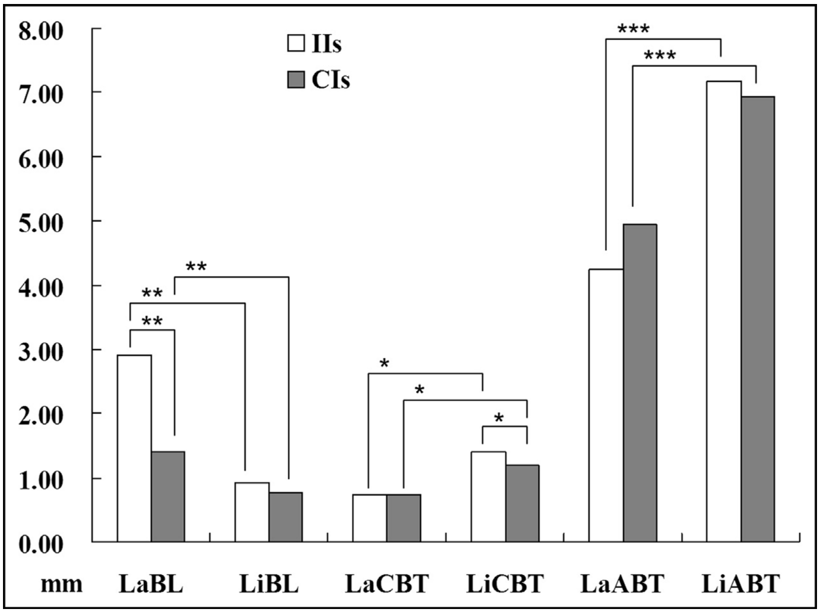

Fig 5. Alveolar bone loss (*BL*) and thickness of the alveolar bone at 1 mm under the alveolar crest (*CBT*) and at the apex (*ABT*) of impacted incisors (*IIs*) and contralateral incisors (*CIs*) after treatment. *La*, Labial side; *Li*, lingual side. **P* <0.05; ***P* <0.025; ****P* <0.0167.

Table V. Alveolar bone development of contralateral incisors (n = 25)

	Pretreatment			*Posttreatment*			
Measurement	*Mean (mm)*	*SD*	*Range*	*Mean (mm)*	*SD*	*Range*	P
LaBL	1.14	0.97	0.00-3.84	1.39	0.98	0.00-4.99	NS*,†
LiBL	0.40	0.47	0.00-1.57	0.76	0.66	0.00-2.96	0.008†
P	0.001*,†			0.002*,†			
%LaBL	12.03	10.74	0.00-41.07	12.68	9.06	0.00-45.49	NS*,‡
%LiBL	3.86	4.32	0.00-13.98	6.71	5.55	0.00-22.70	0.015*,‡
P	0.001*,‡			0.002*,‡			
LaCBT	0.76	0.19	0.49-1.07	0.75	0.20	0.38-1.00	NS*,§
LiCBT	1.23	0.37	0.67-1.97	1.17	0.33	0.71-1.95	NS*,§
P	<0.001§			<0.001*,§			
LaABT	5.24	0.96	2.71-6.98	4.91	1.42	1.53-7.67	NS‡
LiABT	6.91	0.89	5.16-8.32	6.90	1.38	4.56-10.53	NS*,‡
P	<0.001‡			0.001*,‡			
%ABT	196.57	20.74	145.71-237.10	191.29	27.52	142.44-242.67	NS‡

NS, No statistical difference between variables.
*Wilcoxon signed rank test; †adjusted α <0.025 by Bonferroni correction; ‡adjusted α <0.0167 by Bonferroni correction; §α <0.05.

incisors. After the closed-eruption treatment, all 30 impacted incisors were aligned correctly in the dental arches, and the remaining parts of the roots continued to grow into their normal positions. The total posttreatment root length of the impacted incisors (10.66 ± 2.10 mm) did not differ from that of the contralateral incisors (11.04 ± 1.76 mm), a result that was similar to previous findings in 14 patients by Sun et al.[15] As in our study, these authors compared root lengths of surgically exposed (closed-eruption technique) and orthodontically extruded impacted incisors with spontaneously erupted contralateral incisors with CBCT after treatment. They found that the root lengths in the impacted group were 0.46 mm shorter than in the contralateral control group, but the difference was not significant ($P = 0.59$). Their results were measured on the median sagittal section of the crown images. The dilacerated part of the root was rotated, so the actual

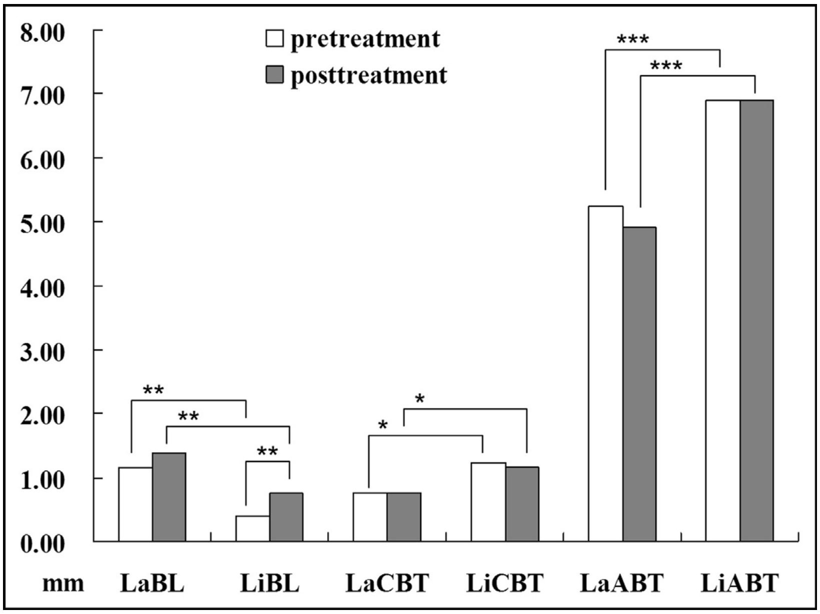

Fig 6. Alveolar bone loss (*BL*) and thickness of the alveolar bone at 1 mm under the alveolar crest (*CBT*) and at the apex (*ABT*) of 25 contralateral incisors before and after treatment. *La*, Labial side; *Li*, lingual side. $^{*}P < 0.05$; $^{**}P < 0.025$; $^{***}P < 0.0167$.

Table VI. Characteristics of the impacted incisors

	Coronal section (N = 30)				*Transverse section (n = 25)*			
Vertical section	*No inclination*	*Mesial inclination*	*Distal inclination*	*n*	*Coronal third*	*Middle third*	*Apical third*	*n*
Labially inclined	4	1	1	6	4	1	0	5
Labially horizontal	2	1	1	4	0	1	1	2
Labially inverted	6	4	0	10	0	4	5	9
Palatally inclined	0	0	2	2	2	0	0	2
Palatally horizontal	0	0	0	0	0	0	0	0
Palatally inverted	1	1	0	2	0	1	0	1
Vertical	2	1	3	6	2	4	0	6
Total	15	8	7	30	9	10	6	25

Vertical section of labially inclined impacted incisors: the crown was labially inclined with the incisal edge in the occlusal direction of point 1 (Fig 3); labially horizontal impacted incisors: the crown was labially inclined, and the incisal edge was level with point 1 (Fig 3); labially inverted impacted incisors: the crown was labially inclined with the incisal edge in the gingival direction of point 1 (Fig 3); palatally inclined impacted incisors: the crown was palatally inclined with the incisal edge in the occlusal direction of point 1 (Fig 3); palatally horizontal impacted incisors: the crown was palatally inclined, and the incisal edge was level with point 1 (Fig 3); palatally inverted impacted incisors: the crown was palatally inclined with the incisal edge in the gingival direction of point 1 (Fig 3); vertical impacted incisors: the crown was not inclined in the vertical section.
Coronal section, mesial inclination: the crown was mesially inclined toward the midline; distal inclination: the crown was distally inclined; no inclination: the crown was not inclined in the coronal section.
Transverse section: We compared the lowest point of the impacted incisors' incisal edge toward the occlusal direction with the roots of the contralateral incisors that had reached the occlusal plane. Coronal third: the impacted incisor's point was within the coronal third of the contralateral incisor's root; middle third: the impacted incisors's point was within the middle third of the contralateral incisor's root; apical third: the impacted incisor's point was within the apical third of the contralateral incisor's root.

length of the dilacerated part on the 3D image might have been longer than indicated on the median sagittal section of the crown images.

Therefore, in this study, we defined the labial and lingual CEJ and the alveolar crest on the median sagittal section of the crown, and the apical point was defined using a 3D image. If root dilaceration was observed, the measurements were calculated in a line following the curvature of the root. The CBCT images were rotated when needed to determine the actual root lengths, and this showed that the root lengths of the impacted and contralateral incisors were almost the same after treatment.

Sun et al[15] also suggested possible explanations for their results: (1) the growth potentials of impacted and control incisors were similar because their root apices had not finished developing, and (2) when incisors that were impacted as the result of a deciduous tooth injury were guided into the dental arch, their Hertwig's epithelial root sheath continued to produce dentin at the same rate as before the injury. We agree with their points. Trauma and chronic periapical periodontitis of the deciduous teeth might put stress pressure on the permanent incisor germs, resulting in dilacerated roots or slowed root development. If the patient grows up without treatment, the consequences might be as follows: the dilacerated part of the roots might be too long to be covered by the alveolar bone, the root lengths of the impacted incisors would be shorter than those of the contralateral incisors, the impacted incisors would be ankylosed or cause a dentigerous cyst, or the impacted incisors would influence the roots of the adjacent teeth. The early closed-eruption technique allows the impacted immature incisors to release some of the pressure on their apices and to fully exploit the growth potential of their roots in order to develop normally in their normal position and to their expected root length. Our results also showed that the remaining part of the dilacerated root was growing toward the long axis of the incisor, and the root length of the impacted incisors was not different from that of the contralateral incisors. Tooth extractions were avoided when the alveolar bone could not cover the whole dilacerated root.

The root length of the contralateral incisors at posttreatment was 2.02 mm longer than their pretreatment values. Many previous studies found that orthodontic traction can influence the root length of adjacent teeth used for anchorage.[11-13] Regarding immature teeth, Mavragani et al[6] studied 280 immature incisors and found no significant difference in root lengthening between those from orthodontically treated patients and those from untreated subjects (age matched); roots that were incompletely developed before treatment showed significantly greater posttreatment lengths than those that were already fully developed before treatment. They speculated that root-forming tissue surrounding the immature incisors could protect the mineralized root tissue from apical resorption during orthodontic treatment. In our study, 33% (10 of 30) of contralateral incisor root apices were in stages 4 or 5 at the onset of treatment; this means that these roots had almost fully developed, and their potential for further lengthening was small. Despite this, the mean contralateral incisor root length for all 30 patients increased by 2.02 mm (22%) during treatment. Twenty-eight of the contralateral incisor root apices were closed after the follow-up period, and no obvious resorption was found, indicating continuous development of the roots. Since the growth potential of immature incisor roots could be fully exploited during the early closed-eruption treatment, the traction force, exerted mainly on the impacted incisors, was small; this decreased the negative effects on both the contralateral anchorage teeth and the impacted teeth.

In this study, root canal widths of the impacted and contralateral incisors significantly decreased during the treatment by 0.28 and 0.22 mm, respectively. These results demonstrated that the pulp of the incisors was alive and continued to produce dentin on the root canal walls. Some researchers have reported that the pulp chamber becomes more restricted with age in the mesiodistal direction, but if restriction occurs at all in the vestibulo-oral direction, its onset is much later in life. This is related to the deposition of tubule-free fibrodentin or secondary dentin at the pulp chamber walls.[16] In our study, the reason for the decrease in root canal width could be that 60 of the examined teeth were immature permanent teeth, which may be more susceptible to treatment-induced changes than are mature permanent teeth. Similar root canal widths for the impacted and contralateral incisors indicated no difference between their levels of root canal growth, before or after treatment.

On the follow-up CBCT image, alveolar bone loss on the labial side and its percentage to root length of the impacted incisors increased significantly compared with the contralateral incisors, whereas the lingual values did not differ ($n = 30$). For both the impacted and the contralateral incisors, the lingual side of the roots had more alveolar bone support than did the labial side. Similar results were reported by Becker et al[2] and Sun et al.[15]

For the 25 contralateral incisors that erupted to the occlusal surface before treatment, labial bone loss was significantly greater than lingual loss; however, the change (0.25 mm) in labial alveolar bone loss during treatment was insignificant, whereas the lingual alveolar bone loss was more substantial at 0.36 mm, a significant difference.

During the surgery, the brackets bonded on the impacted incisors were on the lingual side of those of the contralateral incisors, and the orthodontic force applied on the impacted incisors was toward the labial and coronal sides, whereas the force applied on the contralateral incisors was toward the lingual and apical sides. When the surface of the impacted incisors was exposed in the mouth, new brackets were bonded, and the direction of the traction force was changed. The labial side of the alveolar bone was thinner and more susceptible to orthodontic traction than was the lingual side of the incisors. These may be why the labial sides of the impacted incisors and the lingual sides of the contralateral incisors had more alveolar bone loss. Many previous studies have investigated the probing depths of impacted incisors or canines and adjacent teeth, and increased pocket depths were found in different sites of impacted and adjacent teeth.[2,17-19] Some authors reported that the process of aligning impacted teeth was long and tortuous, altering the structure of the periodontal tissues. In addition, poor oral hygiene during fixed appliance therapy could lead to a buildup of plaque, increasing the risk of periodontal inflammation.[19,20] Crescini et al[17] reported that final periodontal health is the key to evaluating the success of therapy for impacted teeth.

The treatment technique under study here improved the development of the impacted incisor roots, but it did not prevent alveolar bone loss, which is a common complication of orthodontic traction. In terms of root length, the impacted and contralateral incisors were approximately equal, and the difference between them for the percentage of alveolar bone loss on the labial side corresponded to that for labial bone loss. The labial bone loss around the impacted incisors was almost a third of the root length, meaning a clinically significant decrease in bone support. This should be considered when a large amount of tooth movement is planned.

The only statistically significant difference in alveolar bone thickness was between the labial and lingual sides of the incisor roots. The growing conditions of the alveolar bone varied among the patients and might be influenced by many factors. Some studies have found that the thickness of alveolar bone is related to the face height and the occlusion.[9,21] In our study, only 4 patients had a crossbite. We will keep studying the spontaneous development of the alveolar bone of impacted and contralateral incisors as these patients grow after treatment.

The alveolar bone thickness at the apex was 1.82- to 1.93-fold greater than the CEJ width. For the 25 contralateral incisors, alveolar bone thickness did not change significantly during treatment. The total alveolar bone of the incisors was thick and wide. However, if the labial thickness of the alveolar bone surrounding the roots is too thin, or the ratio of the root length surrounded by the alveolar bone to the total root length is too small, the teeth should be treated carefully,[15] and treatment plans relating to tooth movement or periodontal surgery should be modified accordingly.[21] In particular, for teeth with dilacerations along the apical third of the root toward the labial side, a pervasive issue is the potential for iatrogenic damage to the root apex because of extremely thin alveolar bone. Some investigators have suggested that excessive labial or lingual movement of maxillary and mandibular incisors should be avoided to prevent irreversible bone loss, which would leave the tooth with less bone support.[9]

For crown height, some authors have concluded that in spite of the statistically significant differences they found in some periodontal parameters, the overall clinical consequences of these changes were minimal, and that good long-term esthetic results in orthodontic patients can be achieved.[2] In this study, we found that the gingival margin of the impacted incisors was 0.50 mm higher than that of the contralateral incisors after treatment; this was significant statistically, but not clinically. This outcome is similar to the findings of the longitudinal investigation by Crescini et al.[17] The average time between the end of treatment and the final CBCT scan (mean retention period + mean follow-up period) was 16.02 $\pm$ 4.81 months. Further research and longer observations are needed to evaluate the final status of the alveolar bone and the position of the gingival margin.

CONCLUSIONS

In this study, unilateral impacted immature maxillary central incisors were found to develop fully and to the same stage as the control contralateral incisors after closed-eruption treatment. The comparisons of root length and root canal width before and after treatment showed continuously growing incisors without severe root resorption. Both the impacted and the contralateral incisors showed some alveolar bone loss, and thin alveolar bone surrounded the roots; therefore, any orthodontic treatment of the incisors should be planned and undertaken with extra care, particularly when the teeth exhibit dilacerations. Our results are pertinent to growing patients, and growth changes need more study.

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