Alveolar crest regeneration using curvilinear dentoalveolar distraction osteogenesis: a preliminary study

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Objective. The objective of this study was to reconstruct alveolar crest at home position using distraction osteogenesis (DO) with a personalized curvilinear distractor designed through computer-aided technology.

Study design. Five adult dogs were recruited and the maxillary alveolar bone from the first incisor to the first premolar was excised. The dentoalveolar segment adjacent to the defect was osteotomized as a bone transport disk. After 8 weeks of consolidation, the dogs were humanely killed, and the regenerated bone was analyzed.

Results. The DO was successful in the experimental group. The radiographs and histology both verified new bone bridging distraction gap. However, the newly formed bone was located more internally and was not in original position.

Conclusions. The proposed method to reconstruct alveolar crest at home position is improper. The key point was how to maintain the distraction space and hold it at the home position. The barrier membrane technique may be used together with DO to resolve the problem. (Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2011;112:430-438)

Autogenous bone transplantation is the most common surgical method to reconstruct excised alveolar bone; however, this procedure requires a donor site and often results in additional trauma and donor site morbidity to the patient. Therefore, alveolar bone reconstruction without an additional surgery is ideal.

Distraction osteogenesis (DO) is a biological process to generate new bone using graduated tensile stress on divided bone segments based on a tension-stress effect and has emerged as an alternative surgical reconstruction method for bone defects in recent years. This technique was first reported by Codivilla in 1905 for lengthening long bones. Dr. Ilizarov developed and consummated the main concepts and principles, and until 1992, the technique was reported to primarily lengthen human mandibles for modifying hemifacial microsomia and Nager’s syndrome. Since then, numerous articles have reported the application of DO for patients presenting with congenital or acquired craniofacial anomalies.

Recently, dentoalveolar DO has been studied and applied extensively, and involves 2 main aspects: one is the vertical alveolar DO to improve alveolar height to facilitate the insertion of longer implants; the other is the horizontal alveolar DO to enhance alveolar width for insertion of implants with larger diameters. Few studies have reported the reconstruction of excised alveolar bone in a maxillectomy using alveolar DO and there have been no reported methods that can generate alveolar bone within the original bone position using DO, especially for the more frequent cases that have undergone unilateral maxillectomies. Here, we report a preliminary study to verify the feasibility of reconstructing excised alveolar bone using dentoalveolar DO with a personalized curvilinear distractor designed with computer-aided technology. For these experiments, the distractor rail was located strictly along the original alveolar bone.
MATERIAL AND METHODS

Adequate measures were taken to minimize pain or discomfort to experimental animals, and the experiments were conducted in accordance with International Standards on Animal Welfare and in accordance with the ethical standards of the Committee on Animal Experimentation of our institution.

Design and manufacture Of the personalized curvilinear distractor

Five healthy adult dogs (3 male, 2 female, weights 10 to 15 kg) were provided by the Laboratory Animal Center of the Xijing Hospital, the Fourth Military Medical University (Shanxi, China). After anesthesia with an intramuscular injection of ketamine hydrochloride (2.5 mg/kg), coronal computed-tomography (CT) scanning (0.625 mm slice thickness) of the craniofacial skeleton of all the animals was performed with a Bright Speed helical 3-dimensional (3D) CT scanner, and a bite splint was used to separate upper and lower teeth. The CT data were transferred to Mimics 12.0 software (Materialise Group, Leuven, Belgium) so as to reconstruct a 3D model of the craniofacial skeleton, which was saved in STL format (Fig. 1, a).

Next, the 3D craniofacial skeleton was transferred to Pro Engineer 4.0 software (Beijing BPLead Technology, Co, Ltd, Beijing, China) to design a personalized curvilinear distractor. First, representative points of every tooth from the upper right canine to the left second premolar were marked on the labial (buccal) surface of the maxillary alveolar bone, which was set approximately 5 mm apically from the alveolar crest and 2 mm away from the bone surface. Every point was connected to generate a curve, which was smoothed to obtain a guide line for the desired distractor rail (Fig. 1, b).

The guide line was expanded externally and upward as the distractor rail and included a square-bodied bow with a 2.0 × 2.0-mm cross section and a groove created on the convex surface to house the traction cable (Fig. 1, c).

Three stabilizers and a square slider were then designed. Two stabilizers were separately connected and...
matched on the 2 ends of the rail, and were used to fix the distractor onto the maxilla. The third stabilizer was fit with the predicted bone transport disk and connected to the square slider. Each stabilizer included 3 screw holes in a triangular arrangement for 2.0-mm diameter titanium screws. The square slider was designed with a 2.1-mm cross section, 1.0-mm wall, and 3.0-mm length. The slider was encased on the rail with a smooth sliding ability and connected to the third stabilizer (Fig. 1, d). This completed the virtual design for the distractor except for the activation mechanism, which was previously manufactured.

The virtual distractor was processed into a medical-grade titanium device for subsequent animal experiments (Fig. 2). The rail and square slider were processed through numerical controlled wire-cutting technology (Xi’an Tian-sen Machinery and Electronics, Co. Ltd, Shanxi Province, China). The 3 stabilizers were manufactured with precision casting technology (Luoyang Sunrai Ti Precision Casting, Co, Ltd, Henan Province, China). After the square slider was matched to the rail, the 3 titanium stabilizers were soldered onto the rail at the desired position. The activation mechanism and the rail could be assembled together or separated any time needed. There was a rod in the activation mechanism that connected to the square slider through a traction cable (medical-grade nickel-titanium alloy wire with 0.5-mm diameter) in the groove on the convex surface of the rail. Turning the activation rod enabled winding of the cable around the rod. The square slider with the transport disk was then capable of sliding along the rail, with every turn resulting in a 0.5-mm slide. The in vitro simulation of the alveolar bone defect from the left first incisor to the first premolar, including the involved palate (line in Fig. 3, a), as well as the osteotomy of the alveolar bone from the right first incisor to the third incisor (line in Fig. 3, b) for the bone transport disk and the distraction process (Fig. 3, c), were all performed on resin craniofacial skeleton specimens so as to verify the precision and feasibility of the distractor (Fig. 3).

Animal experiments

Each animal was anesthetized with an intramuscular injection of ketamine hydrochloride (2.5 mg/kg), and an additional dosage of ketamine hydrochloride was given according to the condition of the animal during the operation. Prophylactic penicillin (800,000 U) was administered intravenously before incision, and an intramuscular injection of penicillin was continued for 7 days. The dog was laid in a pronated position with the head hyperextended on a head support. The operation was performed under sterile conditions, and the dog was allowed to ventilate spontaneously throughout the whole procedure. The mouth was opened widely, and the opening was maintained with a plastic mouth prop.

A gingival margin incision was made from the mesial side of the left first incisor to the distal side of the first premolar. The incision rose vertically from the 2 ends to the bottom of the vestibulum. The buccal and palatal mucoperiosteum of this portion of the maxilla were separated from the bone surface and reserved completely to expose the maxilla, which was indicated for removal. Two vertical osteotomies were then developed separately between the 2 central incisors (Fig. 4, a) and between the first and the second premolars (Fig. 4, b). The vertical osteotomy between the first and the second premolars turned forward horizontally on the piriform lateral wall to the anterior border of the piriform aperture, and then turned to the right side on the palate to the median palatine suture and turned forward along the palatine suture to the vertical osteotomy between the 2 central incisors. The bone segment was removed, thus creating the alveolar bone defect. The curvilinear length of the buccal surface of the resected alveolar bone was 5 to 7 cm, and the buccolingual dimensions were 1.5 to 2.2 cm. The vertical dimensions were 1.4 to 2.5 cm.

The vertical incision in the buccal alveolar mucoperiosteum between the 2 central incisors turned and extended to the right side and ended at the mesial side of the right first premolar. The buccal alveolar mucoperiosteum was separated downward to explore the area for fixation of the right stabilizer and the bone, so as to create a bone transport disk holding the right first to
third incisors adjacent to the defect. A vertical osteotomy was made through the alveolar ridge between the third incisor and the canine of the right maxilla. The osteotomy extended internally and backward toward the anterior border of the nasopalatine canal, as well as downward toward the palatal mucoperiosteum without a cut-off. The excised alveolar bone segment holding the 3 incisors served as the bone transport disk (Fig. 4, c). On the left residual maxilla, a horizontal incision in the buccal alveolar mucoperiosteum was made posteriorly to the defect to explore the bone for fixation of the left stabilizer. Then, the distractor was matched and fixed on the residual maxilla with 3 titanium screws for each stabilizer (Fig. 4, d). After effective hemostasis and necessary trimming of the reserved mucosa, the buccal and palatal mucoperiosteum were sutured together along the gingival margin. The oronasal partition was reconstructed (Fig. 4, e). The tooth cusps of the bone transport disk and the mandible that impeded the movement of the bone transport disk were stripped down to ensure that the bone transport segment could be distracted to the desired position smoothly (Fig. 4).

Two of the dogs were defined as the control group, in which distractors were fixed but not activated. These animals were humanely killed at 6 weeks postoperatively. The other 3 dogs were included as the experimental group, and after 7 days, the distractors were activated at a rate of 0.5 mm, twice daily, continuously, until the devices could not be further activated. Vertical radiographs of the maxilla were taken weekly to ob-
serve the distraction progression. The 3 dogs of the experimental group were humanely killed after 8 weeks of consolidation. Dogs were killed with an intramuscular injection of an overdose of ketamine hydrochloride. Both the 2 carotid arteries and jugular veins were explored, and the carotid arteries were ligated and cannulated; the jugular veins were kept unobstructed. The head was irrigated with 0.9% physiological saline through the cannulas until the blood was eliminated completely, and a 10% formalin solution was then perfused into the head for fixation. The distractors were removed and the maxilla specimens were separated and fixed in 10% formalin solution for 2 days. Radiographs of the specimens were taken with the parameters of 44 kV, 100 mA, and 125 ms.

CT data of specimens were also obtained to generate 3D models. Each 3D model of a specimen (Fig. 5, a) was overlapped with the corresponding original skeletal model (Fig. 5, b) through specified points congruent in both models using Geomagic Studio 10.0 software (Geomagic Software, Co, Ltd., Shanghai, China) (Fig. 5). In the overlapped models (Fig. 5, c), the original bone was made transparent, and the difference between the regenerated bone and the original alveolar bone could be observed clearly (Fig. 6).

The regenerated bone segments were then decalcified in 10% EDTA for 6 weeks and embedded in paraffin. Sections of 3-μm thickness were made longitudinally in the axial plane, stained with hematoxylin and eosin (H&E) and observed under light microscopy.

RESULTS

All the dogs survived the procedures; however, 1 distractor of the control group became loose and was then removed. Two dogs experienced an incision infection, but were cured through local therapy and an intramuscular injection of penicillin. The distraction periods ranged from 28 to 36 days.

Maxillary radiographs taken during the distraction process indicated that the bone transport segments were distracted smoothly along the rail, reaching their docking site in the experimental group. However, the bone transport disks did not connect to the remaining left alveolar bone. Considerable bone fibers were aligned parallel to the direction of the distraction force in the bone gap. The maxilla radiographs of the experimental group showed that the radiodensity of the regenerated bone was approximately equal to that of the residual alveolar bone of the host maxilla. The control group showed that the bone transport disk was in the original position, and no new bone tissue was regenerated in the defect site (Fig. 7).

Maxillary specimens exhibited continual new bone formation along the distraction gap. The curved dimen-
sions of the regenerated bone on the buccal surface were 2.8 to 3.0 cm, and the buccolingual dimensions were 1.3 to 1.5 cm. The vertical dimensions were 1.2 to 1.8 cm. The regenerated alveolar bone aligned along the arch of the original bone, except that it was located 5 to 8 mm more internally. However, in the control

Fig. 6. An overlapped model, in which the original craniofacial skeleton was made transparent to facilitate observation of the differences between the new bone and the original alveolar bone: a, coronal view; b, palatal view. The overlapped models showed that the new alveolar bone was located more internally as compared with the original bone.

Fig. 7. Maxilla radiographs: a, control group; b, 1 week after distraction; c, 2 weeks after distraction; d, a specimen at 8 weeks.
group, no regenerated bone could be observed in the defect site (Fig. 8).

The overlapped 3D models (Fig. 6) of the specimens and the original maxilla showed that the regenerated bone was along the rail of the original alveolar bone. However, the new bone generated more internally (palatal direction) as compared with the original bone. This result is dissatisfactory, because we expected the new alveolar bone to be located at the home position.

The histology of the regenerated bone showed typical membranous bone formation in the distraction gaps, and no cartilaginous matrix was noted during bone regeneration. In the experimental animal sections, the regenerated bone was mature. The bone trabeculae lost the high orientation along the distraction force, and the woven bone was replaced by lamellar bone. No osteoclasts were seen in the bone matrix (Fig. 9).

**DISCUSSION**

In 2003, Cheung et al. explored the feasibility of reconstructing a posterior maxillectomy with transport distraction. In this study, the dentoalveolar segment adjacent to the defect was osteotomized and distracted backward to the defect, and a new ridge generated in the bone gap. In 2004, Armbruster et al. reported a multidisciplinary approach to restore an acquired palatal defect with DO, orthodontic treatment, and surgical soft tissue flap transplantation, followed with implant insertions into the regenerated ridge and restoration with an implant-supported prosthesis. Niu et al. tried to reconstruct the maxillary defect using alveolar and zygomatic DO in 2009. In the earlier 2 reports, the maxillary defect was small, involving only the posterior alveolar bone defect and did not represent most cases (alveolar bone defects in a unilateral maxillectomy). Moreover, in Cheung et al.’s study, a rectilinear distractor was used, resulting in a new ridge that was not in the original position, the latter of which is necessary to achieve a precise occlusal relation with the mandibular dentition through dentures. In Niu et al.’s study, the curvilinear distractor was used to generate alveolar bone, but the new bone was also not in the home position. Therefore, an emphasis on the position of the bone segment used to reconstruct an alveolar crest defect is important. In view of denture restoration, the home position of the alveolar bone is optimal to rehabilitate the normal occlusion with the corresponding mandibular dentition. Thus, we hypothesized that if the distraction gap generated during the DO process could be located at the position of the original alveolar bone, then the new bone would be at the home position. We also hypothesized that if the distractor rail was designed along the alveolar bone, the bone gap that would occur during the bone transport disk would be distracted and

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**Fig. 8.** Specimens of regenerated bone with an adjacent original maxilla. **a,** No new bone regenerated in the defect site in the control group; **b,** curvilinear new bone regenerated in the defect site in the experimental group (palatal view); **c,** curvilinear new bone regenerated in the defect site in the experimental group (anterior view).

**Fig. 9.** Histology observations of the regenerated bone tissue at 8 week consolidation (H&E stain, original magnification ×100).
moved along the distractor rail at the home position of the alveolar bone. To verify the above hypotheses, we designed this study.

To perform these experiments, a suitable distractor was essential to obtain newly generated bone. However, there were no commercially available curvilinear distractors that could be used to distract bone segments adjacent to the defect cavity to reconstruct curvilinear alveolar bone. To resolve this problem, we designed a personalized curvilinear distractor using computer-aided design technology. To ensure that the regenerated alveolar bone was at the original position, the distractor rail was designed strictly along the bone surface of the original alveolar bone. Then, when the bone transport disk was distracted along the rail, the distracted gap would be approximately at the original position, and after the gap remodeled into bone tissue, the newly formed bone would be in the home position.

We observed that, although the distracted gap was filled with bone tissue, the newly generated curvilinear alveolar bone was located nearly 5 to 8 mm more internally than the original bone. Two main reasons were presumed for this observation. First, the path of distraction was an arc line, so the distraction rate of the external area of the newly generated bone was higher than that of the internal bone. Additionally, some of the external new callus was less immature during remodeling, and this portion resorbed before changing into mature, hard bone tissue. Second, new mucosa regenerated around the bone gap along with bone tissue regeneration. The resultant state of high tensile stress may have pressed the external part of the newly generated bone tissue, compressing part of the bone before it matured into hard bone tissue. Furthermore, the external portion of the regenerated mucosa that was under higher tensile stress may have shifted more internally than the internal portion that was under less tensile stress, and as a result, the bone gap could not be maintained sufficiently. Additionally, the residual gap was displaced internally. These circumstances may have resulted in the new bone generating more internally and in less quantity than the original bone. In a clinical setting, these results would likely cause an alteration of face shape and affect the patient’s quality of life in the future. Thus, our findings indicate that further studies should be performed so as to maintain the size and position of the bone gap that occurs during the DO process. The barrier membrane technique in guided tissue regeneration and guided bone regeneration may be an optimal choice.

In this study, we chose a maxillectomy model according to tooth number, not the actual size, primarily because a surgeon always removes a tumor that is defined in size by the number of teeth it spans. Because the size of the maxillectomy from the first incisor to the first premolar was different for each dog, there was no comparability of the amount of regenerated bone among the different animals. Furthermore, different dogs had different capabilities of bone regeneration. To compare the regenerated bone and the original alveolar bone, we overlapped 3D models of the specimen and the original model of the craniofacial skeleton, allowing an objective assessment of the results.

At the end of the distraction, we observed that the gingival tissue overlying the regenerated bone was continuous with the adjacent natural bone. This result is essential for hygiene maintenance of future dental implants, ensuring a higher survival rate than that of dental implants that are inserted through skin tissue overlying fibula grafts. Because of the regenerated alveolar bone and overlying mucosa, the oronasal fistula that resulted from the maxillectomy diminished greatly. Additionally, because the bone transport disk included a partially hard palate, the newly generated bone also included a newly generated hard palate that replaced the defect cavity. The mucosa overlying the distal section of the bone transport disk was in contact with the mucosa of the mesial section of the left residual alveolar ridge. Thus, the oronasal partition could be reconstructed completely by suturing the 2 parts of the mucosa and suturing the buccal mucosa of the regenerated alveolar bone and mucosa of the cheek, which is better than using the resin palatal plate of the obturator. By suturing the superior edge of the buccal mucosa of the regenerated alveolar crest and the mucosa of the cheek, the vestibular sulcus was reconstructed to facilitate the implant-supported prosthesis.

Notably, the newly generated alveolar bone contained a free end, and such a dental arch may not be able to endure occlusal force after a fixed prosthesis restoration. For clinical patients who have undergone a unilateral maxillectomy, very little alveolar bone remains in the defect site, including loss of the pterygoid process bone, preventing newly generated alveolar bone from joining with residual alveolar bone or the pterygoid process.

In conclusion, if newly generated bone is to form at the original position of the missed curvilinear bone segment, a distraction path that strictly follows along this segment may be improper and subsequently regenerate bone internally. Thus, more studies should be carried out to resolve the presented problems. In particular, the barrier membrane technique may be necessary to maintain the size and position of the distracted gap. Using trifocal DO with only 1 distractor, 1 bone transport disk from a zygoma can be distracted downward and internally, while another bone transport disk from the residual alveolar ridge can be distracted into...
the defect. Ultimately, the 2 newly generated bone structures should join together to circumvent the generation of alveolar bone with a free end.

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REFERENCES

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