Analysis of Skeletal Movements in Mandibular Distraction Osteogenesis

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Purpose: The purpose of this study was to use geometric parameters of movement, calculated from 3-dimensional computed tomography (CT) data, to determine the curvilinear distractor dimensions required to correct mandibular deformities in a series of patients.

Materials and Methods: Preoperative CT scans from 15 patients with symmetric (n = 5) and asymmetric (n = 10) deformities were imported into a CT-based software program (Osteoplan; an open-source visualization application developed by Gering et al at the Surgical Planning Laboratory [SPL, Brigham and Women’s Hospital, Boston, MA]). The software was used to reconstruct virtual 3-dimensional models from these scans. Two experienced surgeons, working with a computer scientist, then used Osteoplan to create an ideal treatment plan for each patient. In each case, the 3-dimensional curvilinear movement was quantified using 4 “parameters of movement” (POMs). These parameters were then used to prescribe a distraction device capable of executing the planned skeletal correction. Curvilinear distractor dimensions calculated by Osteoplan included the radius of curvature of the prescribed device, and the distractor elongation, pitch, and handedness.

Results: Treatment plans including POMs were developed for each patient. The radii of curvature for the prescribed distractors ranged from 2.3 to 14.1 cm, the distractor elongation dimensions ranged from 0.7 to 3.2 cm, and the pitch (horizontal plane) dimensions ranged from 0.005 to 0.8 cm. Handedness was either a left (n = 12) or right (n = 8) turning helix.

Conclusion: The results of this study indicate that, using geometric parameters of movement calculated from 3-dimensional CT scans, curvilinear devices could be prescribed for correction of the range of skeletal deformities in this group of patients.

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Distraction osteogenesis (DO) is a promising alternative to traditional methods of bone lengthening for correction of congenital and acquired cranio-maxillofacial deformities. Since 1992, the technique of DO has been used with increasing frequency for bony expansion in patients with skeletal abnormalities of great magnitude and complexity.1-6

Multidirectional (3-dimensional) distraction is required for most cranio-maxillofacial corrections. Cur-
rently, these movements are accomplished with the use of an externally placed multivector distraction device made up of sliding and hinge joints. Alternatively, the surgeon manipulates the regenerate (ie, changes the jaw position) after distraction but before complete bone healing.7

Multidirectional distraction movements have conventionally been described as a series of separate translations and rotations in the sagittal, transverse, and vertical planes. However, using the “Perpendicular Bisector Theorem” based on postulates from Euclidean geometry, it can be shown that in a 2-dimensional reference plane, combinations of translational and rotational movements can be resolved into a single curved path that moves about a unique axis of rotation.7 Therefore, any movement of a bony segment that has translational and rotational components can be resolved into a simple rotation around a unique axis. This axis can be calculated by the clinician manually or with the aid of a software package.8 Seldin et al7 and others9 have previously reported semiburied, curvilinear, fixed trajectory, miniature distraction devices that are capable of producing such curvilinear movements.

Because most craniomaxillofacial corrections are 3-dimensional (3D) in nature (sagittal, coronal, and horizontal planes), a single radiograph (eg, a lateral cephalogram) is insufficient to produce a complete description, analysis, and treatment plan for the deformity.10,11 To address this problem, a CT-based 3D treatment planning software package was developed.8 It allows a surgeon to create an accurate preoperative treatment plan for multidirectional correction of facial skeletal deformities. The software has been customized for DO so that it can be used to determine the required curvilinear vector of movement and to calculate a prescription for a specific curvilinear distraction device.

It is not known whether a custom-made distraction device will be required to carry out the unique skeletal correction for every patient or whether the majority of corrections can be adequately addressed using a finite family of devices. We hypothesize that a finite number of devices with some variation in placement will allow for the correction of most clinical deformities. As a first step to answer this question, the purpose of this study was to use geometric parameters of movement, calculated from 3D CT data, to determine the curvilinear distractor dimensions required to correct mandibular deformities in a series of 15 patients.

**Materials and Methods**

Preoperative computed tomographic (CT) scans from 15 patients with complex asymmetric (n = 10) and symmetric (n = 5) mandibular deformities were obtained from 2 centers: Massachusetts General Hospital (Boston, MA) and University of Texas at Houston (Houston, TX). Each CT scan was imported into the Osteoplan module of the 3D slicer,12 an open-source visualization application developed by Gering et al12 at the Surgical Planning Laboratory (SPL, Brigham and Women’s Hospital, Boston, MA).

The software was used to segment and reconstruct bony structures. During segmentation, the mandible was separated from the skull base via a semi-automated labeling process. The reconstruction procedure then used the marching cubes method13 and a triangular surface decimation function to reconstruct the surface models of the mandible and skull base (Fig 1). Three landmarks were identified on the mid-sagittal plane including menton, nasion, and anterior nasal spine. In addition, right and left orbitale were identified on the horizontal plane. The treatment planning software then aligned these landmarks, and the associated skeletal models, to the true vertical and horizontal planes using a least-squares fit algorithm.

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The treatment planning process involved making simulated osteotomies on the models and then repositioning the resultant fragments into the desired final positions (Fig 2).8,10 Multiple treatment plans were developed for each patient by an oral and maxillofacial surgeon and a computer scientist. These plans could be superimposed for comparison. A final treatment plan was chosen by the sur-
The software system was then used to calculate the curvilinear path of motion for each skeletal correction (both sides in bilateral cases). The 4 parameters of motion (POMs) which fully define this curved movement path are (Fig 3): 1) location and orientation of an anatomical axis of rotation within a 3D coordinate system encompassing the anatomic object of interest; 2) angular displacement around this axis; 3) pitch, or the movement along the axis that accompanies the angular displacement; and 4) handedness (ie, a right- or left-handed helix).

The treatment planning system uses the POMs in combination with the surgeon’s decision about distractor placement on the mandible to prescribe the dimensions of a specific curvilinear distraction device for each patient. The 4 dimensions that uniquely describe a curvilinear distraction device are (Fig 3): 1) radius of curvature, measuring the distance from the axis of rotation to the proposed centerline of the distractor; 2) distractor elongation, defined as the arc length of planned movement measured along the centerline of the distractor; 3) pitch, defined as the translation along the axis of rotation that accompanies the angular displacement; and 4) handedness, indicating whether the helical movement is right- or left-handed.

The dimensions of the distraction devices were tabulated and analyzed to determine the devices that would have been required to treat the 15 patients included in this study using curvilinear distraction.

Results

Skeletal deformities were analyzed and models created for 15 patients with hemifacial microsomia (n = 10), Treacher Collins syndrome (n = 2), and post-traumatic defects (n = 3). The segmented mandibular fragments were moved to the desired position as determined by the surgeon. Coronoidectomies were planned in 6 cases to avoid bony collision. The software prescribed a curvilinear distractor that could achieve a satisfactory skeletal correction for each case. The geometric parameters of movement were calculated for each plan: anatomic location of the axis of rotation; angular displacement (mean, 15.8°; range, 6.5°-38.3°); pitch (mean, 0.18 cm; range, 0.005-0.8 cm); and handedness was either a left (n = 12) or right (n = 8) turning helix.

The mean radius of curvature for all the distractors was 5.7 cm with a range from 2.3 to 14.1 cm. The asymmetric patients required distractors with radii of curvature ranging from 4.0 to 14.1 cm, with a mean of 7.8 cm, while those with symmetric deformities required a range from 2.3 to 7.0 cm, with a mean of 3.6 cm. The distractor elongation parameter ranged

**FIGURE 2.** Cutting tool function performed by the surgeon with the 3D mouse and cutting tool. A, The movable coordinate system, represented by the colored arrows, allows movement of models in 3D space. The cutting tool, represented here by a simple rectangular actor (red), represents the osteotomy. The movable coordinate system can be attached to anatomic models or to the cutting tool for translation or rotation of these actors about the 3 defined axes. To simulate osteotomies, the cutting tool is positioned with respect to the mandible using the movable coordinate system. Once the desired position is achieved, the cut operation is applied and 2 topologically closed models are created. B, The proximal and distal fragments are labeled and color-coded to permit superimposition. The proximal fragment (red) and the distal fragment (blue) are moved to their desired positions using the movable coordinate system. Note, because of bony interference (“collision”) a virtual coronoidectomy was performed.

from 0.7 to 3.2 cm with an overall mean of 1.6 cm. The asymmetric patients required distractor elongations ranging from 0.9 to 2.7 cm, with a mean of 1.6 cm, while the symmetric patients required a range from 0.7 to 3.2 cm, with a mean of 1.5 cm. Finally, the pitch parameter ranged from 0.005 to 0.8 cm with an overall mean of 0.18 cm. The asymmetric patients required pitches ranging from 0.005 to 0.4 cm, with a mean of 0.15 cm, while the symmetric patients required a range from 0.008 to 0.8 cm, with a mean of 0.2 cm. These dimensions must be considered in combination with the location of the prescribed axis of rotation to determine the actual bony movement.

**Discussion**

In the 15 cases analyzed in this study, the radius of curvature parameter exhibited the largest range of variability, from 2.3 to 14.1 cm. Because the position and orientation of the axis of rotation is the POM that determines the magnitude of the radius of curvature, the axis of rotation is clearly the most important of the POMs as an indicator of distractor prescription.

Angular displacement and radius of curvature jointly determine the requisite distraction gap and thus the required distractor elongation. The elongation parameter varied from 0.7 to 3.2 cm. This suggests that if all curvilinear distractors were manufactured with a length of about 3.5 cm, the track could be trimmed for cases requiring less elongation. The shorter the elongation parameter, the lesser the sensitivity to radius of curvature; a straight line distractor being a reasonable approximation of larger radii of curvature over a short distance.

The pitch parameter (horizontal plane) ranged from 0.005 to 0.8 cm. Pitch is the parameter of movement that adds the most to the mechanical complexity of the distraction device. It is important...
to note that a distractor with a small pitch can cause a large transverse movement (Fig 4).

Other laboratories have developed semi-buried multidirectional distraction devices to address the need for 3D control of craniofacial distraction movements. Triaca et al’s multiaxis intraoral distractor produces explicit horizontal, vertical, and rotational movements in the parasagittal planes. This distraction device also allows for mid-line correction via an additional procedure. Walker et al’s bi-directional buried mandibular distractor allows for mediolateral adjustments during bilateral sagittal mandibular distraction. Finally, Schendel et al’s spiral distractor allows for movement in a logarithmic spiral pattern that is said to mimic the pattern of bone growth.9,14

Each of these semi-buried devices accomplishes the goal of multiplanar distraction without the disadvantages of external devices. None of these distractors has been reported as being coupled with an accurate 3D treatment planning system. Although the multi-axis intraoral distractor and the bi-directional buried mandibular distractor both allow for mid-course adjustments, preoperative analysis of the parameters of motion would allow surgeons to compare multiple treatment plans so that the optimal vector of motion could be accurately chosen preoperatively.

In our approach to DO, the curvilinear distractor must be chosen by means of a 3D treatment planning system to determine which specific distraction device would be most appropriate for the selected treatment plan and where the chosen device must be placed on the skeleton. The treatment planning software system allows surgeons to visualize the 3D curvilinear motion. It also reveals bone interferences that may not otherwise be apparent.10 The software gives the surgeon a means of comparing multiple treatment plans.

Problems still to be solved include the inability to determine occlusion with a high degree of accuracy on 3D CTs. This currently limits the use of 3D treatment planning to relatively severe cases in which attaining optimal occlusion is not the primary objective. This deficiency arises from the inability of CT imaging to accurately represent dentition and from the lack of tactile feedback in some software planning systems. Work has begun to address this limitation by improving visualization of the teeth.17-20 Currently, the time and computer expertise required to produce a treatment plan is a significant barrier for most surgeons. The lack of a fourth dimension in treatment planning, the dimension of growth, also limits the applicability of the system. Another limitation is the lack of soft tissue representation. Finally, navigation systems to facilitate the intraoperative implementation of treatment plans are essential to fully realize the benefits of a 3D treatment planning system.

Continuing efforts in the development of our 3D treatment planning system have been directed at addressing these issues. The integration of laser scans and improved reconstruction methods will be used to address the lack of accurate dental data. Simplified user interfaces will help to streamline the planning process to ease the learning barrier for surgeons. Efforts are also being directed at integrating CT-guided navigation systems for intraoperative navigation.

We hypothesize that a finite number of devices (rather than an infinite number of custom-made ones) with variation in placement will allow for the correction of most clinical deformities. As a first step to confirm this hypothesis, the purpose of this study was to use geometric parameters of movement, calculated from 3D CT data, to determine the curvilinear distractor dimensions required to correct mandibular deformities in a series of 15 patients. In a subsequent study, we will calculate and test the exact family of curvilinear distractors required for most mandibular corrections.

References

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