# Range of Curvilinear Distraction Devices Required for Treatment of Mandibular Deformities

*Lutz Ritter, MD,* Krishna Yeshwant,†*
*Edward B. Seldin, DMD, MD,‡ Leonard B. Kaban, DMD, MD,§*
*Jaime Gateno, DMD, MD,‖ Erwin Keeve, PhD¶*
*Ron Kikinis, MD,# and Maria J. Troulis, DDS, MSc***

**Purpose:** The purpose of this study was to determine the range of fixed trajectory curvilinear distraction devices required to correct a variety of severe mandibular deformities.

**Materials and Methods:** Preoperative computed tomography (CT) scans from 18 patients with mandibular deformities were imported into a CT-based software program (Osteoplan). Three-dimensional virtual models of the individual skulls were made with landmarks to track movements. An *ideal treatment plan* was created for each patient. Upper and lower boundaries for the dimensions of curvilinear distractors were established based on manufacturing and geometric constraints. Then, anatomically acceptable distractor attachment points were identified on the models using proximal and distal grids. *Treatment plans* were simulated for a series of distractors with varying radii of curvature, elongations (arc-length of device), and placements along the grids. The outcomes using these distractors were compared with the ideal treatment plans. Discrepancies were quantified in millimeters by comparing landmarks in the simulated versus ideal movements.

**Results:** Approximately 400,000 simulated 3-dimensional movements, based on the distractor parameters and variations in placement were computationally evaluated for the 18 cases. It was determined that, by varying distractor placement, a family of 5 distractors, with 3, 5, 7, and 10 cm radii of curvature and a straight-line device, could be used to treat all 18 cases to within 1.8 mm of error.

**Conclusions:** The results of this study indicate that a family of 5 curvilinear distractors may suffice to treat a broad range of mandibular deformities.

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Distraction osteogenesis has become a well-established technique for the correction of craniomaxillofacial deformities.[1-3] It is generally accepted that most mandibular corrections require multidirectional movements.[4,5] Complex skeletal corrections are currently achieved by using external distraction devices

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*Research Fellow, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA.

†Research Fellow, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA.

‡Associate Professor, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA.

§W.C. Guralnick Professor and Chairman, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA.

‖Associate Professor, Department of Oral and Maxillofacial Surgery, Dental Branch, University of Texas at Houston, Houston, TX.

¶Head, Surgical Systems Laboratory, Center of Advanced European Studies and Research (CAESAR), Bonn, Germany.

#Associate Professor, Radiology, Director, Harvard Surgical Planning Laboratory, Brigham and Women's Hospital, Boston, MA.

**Associate Professor and Director of Minimally Invasive Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA.

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Address correspondence and reprint requests to Dr Troulis: Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, 55 Fruit Street, Warren Building 1201, Boston, MA 02114; e-mail: mtroulis@partners.org

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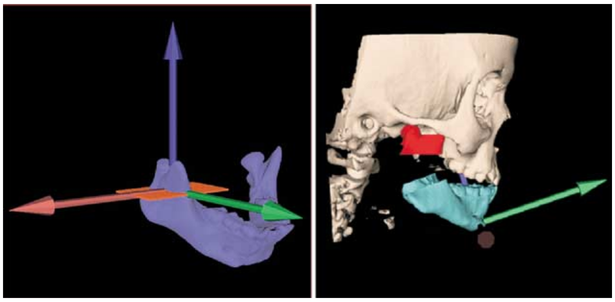

**FIGURE 1.** The surgeon uses a 3D mouse to position the virtual cutting tool, represented by a red rectangle. Having achieved the desired position, the virtual osteotomy is performed (*left*). After the osteotomy, the surgeon moves the distal fragment (shown in red) to its desired final position apart from the proximal fragment (shown in blue), representing the ideal treatment plan (*right*).

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with interposed joints and angles. These devices permit mid-course alterations in the vector of movement. In addition, the surgeon may manipulate the newly positioned jaw, prior to skeletal healing, thus molding the regenerate.[6] A multidirectional semiburied distraction device has also been reported.[7]

We previously reported that a semiburied curvilinear distractor design is a potentially promising approach for multidirectional mandibular distraction.[6] Curvilinear devices are based on the concept that a series of translational and rotational movements made in 3 dimensions (sagittal, coronal, and horizontal planes) can be summed to produce a simple curved path capable of correcting a complex multiplanar deformity. However, because midcourse corrections are not possible with buried curvilinear devices, our laboratory developed a 3-dimensional (3D) treatment planning system to determine preoperatively the correction required for each patient's deformity.[8] In a previous study, we also calculated the 4 distractor dimensions that are required to describe curvilinear devices.[9] The purpose of this study was to determine and test *the exact number of curvilinear distraction devices* that would be required to correct a variety of mandibular deformities.

## Materials and Methods

Preoperative computed tomography (CT) scans from 18 patients with complex asymmetric (n = 10) and symmetric (n = 8) mandibular deformities were obtained from 2 centers: University of Texas at Houston and Massachusetts General Hospital. Osteoplan and 3-D Slicer software packages[10,11] (see also www.slicer.org) were used to reconstruct virtual 3D models of each patient's skull base and mandible from the CT scans.[8,12] Experienced surgeons (L.B.K., M.J.T.), working with computer scientists (K.Y., L.R.), used Osteoplan to create *ideal treatment plans* for each case by simulating mandibular osteotomies on the models and repositioning the resultant proximal and distal fragments into the desired final positions (Fig 1). Landmarks were placed on each of the repositioned distal fragment models at the cusp tips of the left and right molars, the incisor tip, and pogonion (Fig 2).

### CURVILINEAR DISTRACTOR DIMENSIONS

Four dimensions must be specified to fully characterize each device in a family of curvilinear distractors.[9] These dimensions are the *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 (Fig 3).

### DETERMINING BOUNDARIES ON CURVILINEAR DISTRACTOR DIMENSIONS

Using 4 of the 18 preoperative cases, 2 unilateral and 2 bilateral, upper (largest) and lower (smallest) boundaries were determined for each dimension to establish the spectrum of devices to be considered for inclusion in the curvilinear distractor family.

The lower boundary for the radius of curvature dimension was determined by manufacturing limitations. The upper boundary was defined as the radius

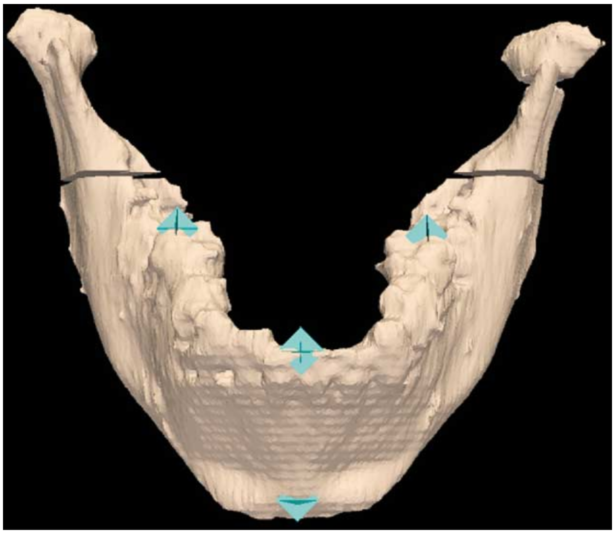

**FIGURE 2.** Skeletal movements made in the treatment planning system were tracked using 4 landmarks that were identified on the cusp tips of the left and right molars, on the incisor tip, and on pogonion. The landmarks move along with the skeletal fragment.

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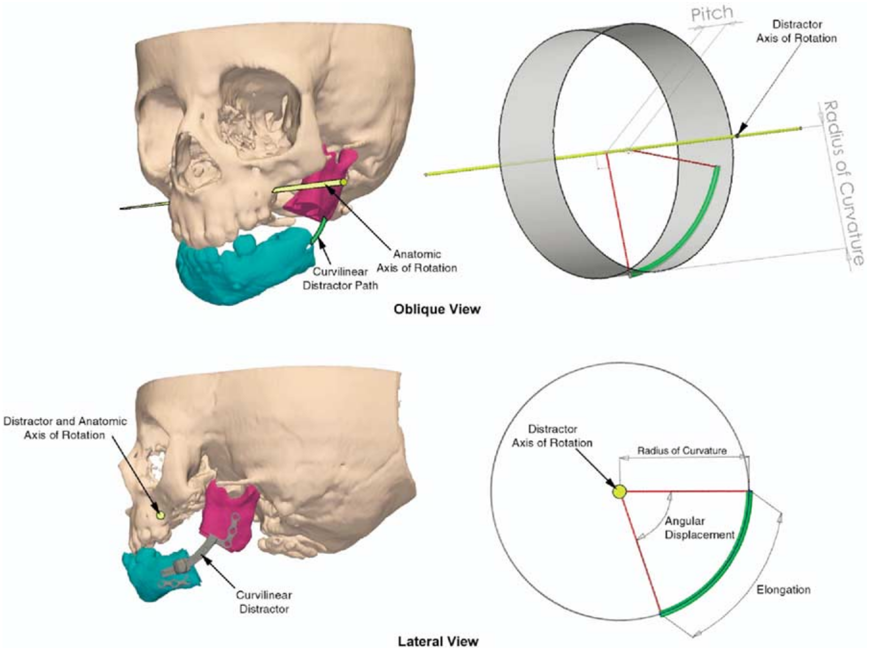

**FIGURE 3.** In this figure, the path of motion is represented by the bright green band. This curvilinear movement is based on the location of the axis of rotation, which is represented by the yellow cylinder. The motion is also based on the angular displacement, the pitch, and the handedness of the movement. The path illustrated here is based on a right-handed helix. Note that the pitch is emphasized in this figure for illustration. The actual pitch for this patient was very small.

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at which curved distraction becomes indistinguishable from straight-line distraction (Fig 4). This was determined by using the treatment planning software to compare straight-line distractions of 1 cm and 4 cm with a series of simulated curved distractions. Next, curved distractions with elongations ranging from 0.5 cm to 3.5 cm in 0.1-cm increments were simulated in each of the cases. The curved distractions began at the lower boundary of the radius of curvature dimension and increased in 1-cm increments until a curved movement was found that had a curvature large enough to approximate straight-line distraction. Landmarks were used to compare the outcomes of the straight-line and curved distractions. All of these movements were made by simulating devices attached to the virtual skeletal fragments in identical locations and these simulated movements were termed a *predicted plan*.

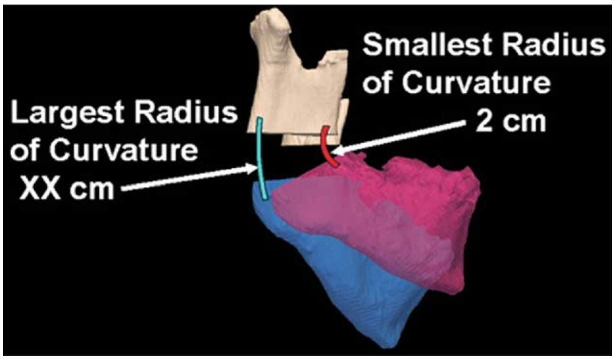

**FIGURE 4.** This figure schematically illustrates the maximum range of movements that physical curvilinear distractors can make. The movement shown in red represents the lower limit of the radius of curvature parameter. The upper limit of the radius of curvature parameter is shown in green. Although this upper limit was unknown, it was theoretically defined as the curvature at which curvilinear distraction becomes indistinguishable from straight-line distraction.

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To compare the *predicted plans,* the treatment planning software calculated the cumulative average distance between associated landmarks. It was arbitrarily decided that if the cumulative distance between all of the associated landmarks was less than 2 mm, then the outcomes could be considered clinically indistinguishable. In this study, it was assumed that an equal number of right- and left-handed distraction devices would be needed in the family of curvilinear distractors.

## IDENTIFYING THE MEMBERS OF THE FAMILY OF DISTRACTORS

In the next step, the treatment planning system was used to determine the ranges of radii of curvature that a single potential member of the family of distractors could cover by varying position and elongation. This was iterated for 13 potential members of the family of distractors. First, 2 × 2 mm grids covering anatomi-

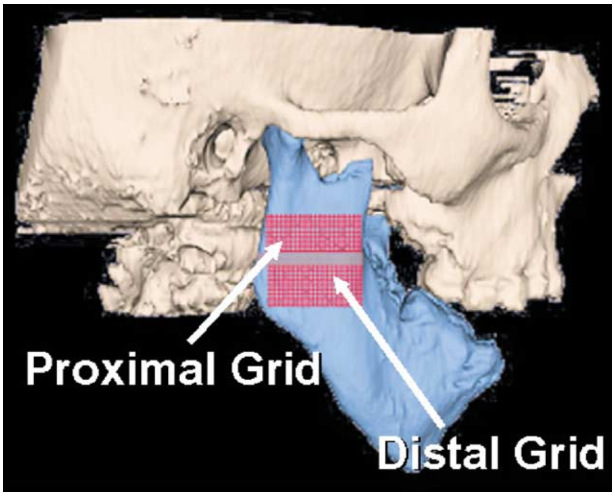

**FIGURE 5.** To vary the placement of each simulated device, 2 × 2 mm grids were created on the proximal and distal portions of the mandible covering anatomically acceptable attachment points for the footplates of distraction devices, as shown in this image. Movements were then produced by attaching a curvilinear device to every combination of proximal and distal points within those grids.

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cally acceptable attachment points for the footplates of the distraction devices were created on the proximal and distal fragments in each of the 4 cases used earlier (Fig 5). Then, geometrical positions of the distal fragment at the endpoint of distraction were simulated for 2-cm and 4-cm elongations using distractors with radii of curvature from 3 cm to 15 cm in 1-cm increments. Attachment points for the devices were positioned in the middle of the grid of anatomically acceptable attachment points. Changes in position of the landmarks were used to record each outcome. These simulations were used as reference simulations representing the potential distractors for the family of curvilinear distractors.

For the same 4 cases, geometrical positions of the distal fragment at the endpoint of distraction were simulated with systematically varying attachment points, distractors, and elongations. Increments of 2 mm were chosen for the different attachment points along the defined grid. For the distractors, the radius of curvature was varied from the lower bound to the upper bound in 5-mm increments. Elongation was varied in 1-mm increments from 5 mm to 100 mm. These simulations were used as test simulations to approximate the range of radii of curvature that a potential member of the family of distractors could cover. The distractors used here were termed comparison distractors.

Each simulated outcome of the potential member of the family of distractors was compared with simulated outcomes of the comparison distractors using the defined landmarks. Thereby, the range of radii of curvature of the comparison devices was determined that achieved the same distraction as the potential member of the family of distractors. Analyzing these ranges for each potential member of the family of distractors revealed overlap of the determined ranges allowing us to identify redundant distraction devices (Fig 6).

### TESTING THE CURVILINEAR DISTRACTOR FAMILY

Treatment plans were created for all 18 cases using only devices from the established family. The cumulative distance between associated landmarks was used to compare the resultant position of the distal fragments to the ideal treatment plans initially produced. If the average distance between landmarks was less than 2 mm, then the placement produced by the device from the family was considered acceptable.

## Results

Three-dimensional models were successfully reconstructed for all cases in this study. The skeletal deformities were analyzed and treatment plans were created for 18 patients with hemifacial microsomia (n = 10), bilateral facial microsomia (n = 1), Treacher Collins syndrome (n = 4), and posttraumatic deformities (n = 3). Coronoidectomies were performed in 6 cases to avoid bony collision as indicated by Osteoplan.

The manufacturing process imposed a 2-cm lower boundary on the radius of curvature dimension. A 15-cm upper boundary on the radius of curvature

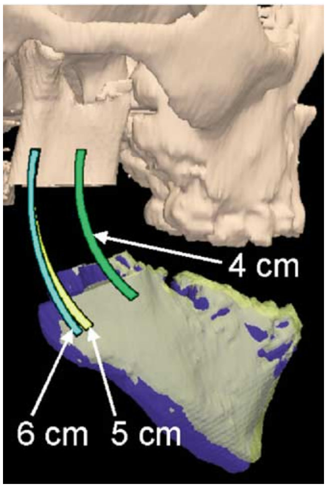

**FIGURE 6.** In this image, the 5-cm (yellow distal fragement) and 6-cm (blue distal fragment) devices are placed in similar positions and produce nearly identical movements at this elongation. In addition, the 4-cm and 5-cm devices produce identical movements, although these distractors are positioned in different places.

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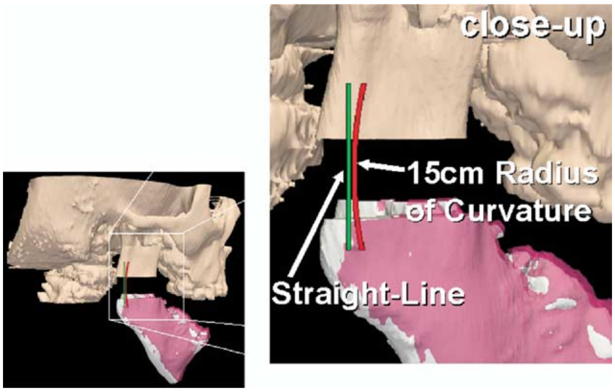

**FIGURE 7.** These images show the movement produced by a curvilinear device with a radius of curvature of 15 cm, represented in red, and a straight-line device, represented in green. The resulting positons of the distal fragments are shown superimposed in red for the 15-cm curvilinear device and in white for the straight-line device.

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dimension was found to approximate a straight-line device (Fig 7). The elongation boundaries ranged from 1 cm to 4 cm, and the pitch boundaries, from 0.0 cm to 0.8 cm.

A set of distractors with radii of curvature ranging from 3 cm to 15 cm in 1-cm increments at both 2-cm and 4-cm elongations was analyzed. The curvilinear movement simulation algorithm was used to computationally evaluate approximately 400,000 simulated outcomes for the 18 cases (Fig 8). By eliminating devices with overlapping movement ranges, it was determined that a family of curvilinear distractors, with radii of curvature of 3, 5, 7, and 10 cm, and a straight-line device, would suffice to treat most deformities requiring curvilinear movements. Members from this family of devices were successfully used to simulate the ideal treatment all 18 cases. The maximum error produced by any device was 1.8 mm (Fig 9).

## Discussion

The results of this study indicate that a custom-made curvilinear device is not required for each patient. Rather, a kit of 5 curvilinear distractors could be used to treat most severe mandibular deformities. Using such a kit would improve the applicability of curvilinear distraction through reduced manufacturing costs and increased accessibility. In the approach to distraction described in this study, a specific curvilinear device is chosen using a 3D CT-based treatment-planning program. An intraoperative navigation system would ideally guide the surgeon to accurately place the distraction device. This is important because errors in distractor orientation could result in large skeletal discrepancies and buried, miniature devices do not permit mid-course correction. Our group is currently working on integrating existing CT-based navigation systems with the treatment planning software developed for this project.

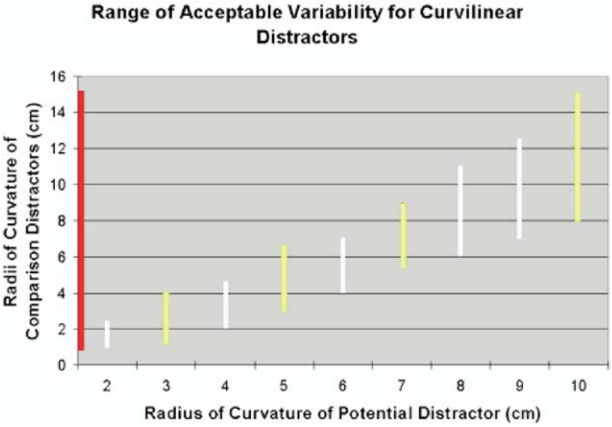

**FIGURE 8.** Vertical band represents the range that each distractor can cover. For instance, a distractor with a 2-cm radius of curvature was found to adequately approximate movements produced by devices with radii of curvature ranging from 1 cm to 2.5 cm. The yellow bands represent the movements of a set of distractors that can be used to cover the broadest range of movements with minimal redundancy. The 3-cm and 5-cm distractors cover a range of movements that eliminate the need for a 4-cm device. Similarly, the 5-cm and 7-cm distractors remove the need for a 6-cm device, and the 7-cm and 10-cm distractors remove the need for an 8-cm device. The red band on the left hand side of the slide shows the total range that this family can cover.

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Because many patients undergoing distraction osteogenesis are growing children, future studies must incorporate growth data into the treatment planning process. In the future, we also plan to repeat this study in cases with less severe craniofacial deformities to determine the tolerable magnitudes of error and whether the same range of devices will be applicable. Furthermore, soft tissue simulation and high-resolu-

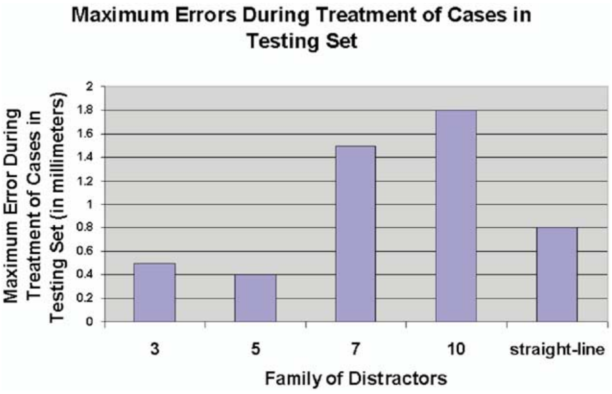

**FIGURE 9.** Maximum error, in millimeters, produced by each of the devices in the distractor family during treatment of all 18 cases. The maximum error produced by any device was 1.8 mm.

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tion capture of the dentition must be included to make the treatment planning software more accurate for planning less severe cases.

The results of this study indicate that a family of curvilinear distractors, with radii of curvature of 3, 5, 7, and 10 cm and a straight-line device, would suffice to treat a broad range of mandibular deformities to within 1.8 mm of an ideal treatment plan.

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