### **Original Article**

# A finite element study on the effects of midsymphyseal distraction osteogenesis on the mandible and articular disc

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#### ABSTRACT

**Objective:** To evaluate the biomechanical effect of midsymphyseal distraction osteogenesis with three types of distractors on the mandible and articular disc using a three-dimensional finite element model analysis.

**Materials and Methods:** A virtual model of the mandible was produced from computed tomography scan images of a healthy 27-year-old man. On the finite element model of the mandible, expansion of the bone-borne, tooth-borne, and hybrid type distractors were simulated with the jaw-closing muscles. The displacement and stress distribution of the mandible and articular disc were analyzed.

**Results:** With the bone-borne appliance the alveolar process area was displaced more than the basal bone area. The tooth-borne appliance displaced the mandibular body in a parallel manner and showed high level of the von Mises stress in the alveolar process and the ramal region as well as in the condylar neck area. The hybrid type showed medium amount of displacement and stress distribution compared with the bone-borne and tooth-borne type. At the articular disc the compressive stress was concentrated in the anteromedial and posterolateral area, and it was highest in the tooth-borne distractor, followed by hybrid appliance and bone-borne appliance.

**Conclusions:** The tooth-borne distractor produced more parallel bony widening in the midsymphyseal area and larger expansion in the molar region; however, it induced higher stress concentration on the articular disc than the hybrid appliance and bone-borne appliance. Whether any long-term side effects on the temporomandibular joint are anticipated, especially in tooth-borne distractor, remains to be investigated. (*Angle Orthod.* 2012;82:464–471.)

**KEY WORDS:** Articular disc; Displacement; Finite element analysis; Mandible widening; Midsymphyseal distraction osteogenesis; Stress distribution

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#### INTRODUCTION

Ilizarov<sup>1</sup> developed the protocols of distraction osteogenesis (DO) and applied them to orthopedic surgery. The application of DO to the field of the maxillofacial surgery was first attempted in the 1970s for lengthening of the mandible.<sup>2,3</sup> DO is also a useful method for patients with severe maxillomandibular basal bone discrepancy.<sup>4</sup> In growing patients with moderate transverse mandibular deficiencies, orthodontic expansion appliances such as lip bumpers,<sup>5</sup> Schwarz appliances,<sup>6</sup> or functional appliances<sup>7</sup> are recommended. On the other hand, in adults with severe crowding due to transverse skeletal deficiency in mandible, midsymphyseal DO has been used as surgical aids for nonextraction orthodontic treatment.<sup>8–10</sup>

The expansion appliances for the midsymphyseal DO can be classified as bone-borne, tooth-borne, and hybrid (bone- and tooth-borne) types. There are controversial opinions about the effects according to

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the type of distractors. Del Santo et al.<sup>10</sup> found that with a tooth-borne distractor, the alveolar bone is expanded more than the basal bone. However, Tae et al.<sup>11</sup> reported that a tooth-borne distractor induced parallel expansion and a hybrid distractor disproportional expansion. In contrast, King et al.<sup>9</sup> observed in their clinical report that a hybrid type distractor produced a parallel widening of the dento-osseous segments.

There are some reports about the effect of midsymphyseal DO on the temporomandibular joint (TMJ). In clinical study, degenerative changes of the TMJ caused by midsymphyseal DO seem to be rare events. Guerrero et al.4 expanded 10 patients using a toothborne distractor or a bone-borne distractor, and only one patient had transient TMJ pain and dysfunction during the stabilization period caused by transient occlusal instability. On the long-term evaluation, Kewitt and Van Sickels<sup>12</sup> reported that preoperatively 47% of the patients had TMJ symptoms, but no patient had symptom worsening or developed new symptoms postoperatively. However, biomechanically, mandibular widening with midsymphyseal DO can induce rotation of the condyle.<sup>13,14</sup> Samchukov et al.<sup>13</sup> employed a computer model and found that the condyle rotates 0.34° per millimeter during midsymphyseal widening. And in animal study, Harper et al.<sup>14</sup> found the morphologic and histologic changes within the fibrous layer, cartilage layer, or bone/cartilage interface and concluded that the severity of these changes was correlated with the likely rotational forces directed at the condyle.

The finite element analysis (FEA) is a powerful tool to analyze biomechanical changes in complex geometric parts of the human skeleton.<sup>15</sup> Considering that the mandible is supported with the soft tissue envelope of surrounding structures such as muscle, skin, and ligaments of condyle, FEA has the advantage of being able to simulate the masticatory muscle force. However, only a few FEA studies have focused on biomechanical changes that occur in the mandible and condyle after midsymphyseal DO.<sup>16,17</sup>

Basciftci et al.<sup>16</sup> evaluated the biomechanical effects of mandibular midline DO; however, there is no information about simulating masticatory muscles and the differences between the distraction device types. Boccaccio et al.<sup>17</sup> analyzed the displacement of mandible for three types of midsymphyseal DO devices with and without the mastication forces; however, they did not focus on the mandibular condyle and articular disc, but the stability of each appliance. Consequently, very little information is available about the biomechanical effect of midsymphyseal DO on the mandible and articular disc in various types of distractors. The purpose of this study was to evaluate the biomechanical effect of midsymphyseal distraction osteogenesis with the three types of distractors on the mandible and articular disc using a three-dimensional (3D) finite element model analysis.

#### MATERIALS AND METHODS

Computed tomography (CT, Shimadzu Corp, Tokyo, Japan) with a high resolution bone algorism, 120 kVp, 230 mA, 1:1.2 pitch and a scanning time of 1.5 seconds, and a slice thickness of 1 mm, was taken on the mandible of a healthy 27-year-old man with no craniofacial anomaly. CT images were converted to digital imaging and communications in medicine (DICOM) files that effectively support the communication with various digital imaging systems, and cancellous bone, compact bone, teeth, and periodontal ligament were manually distinguished.

The protocols of this study were approved by the Ethics Committee of the Gangneung-Wonju National University Dental Hospital (IRB 2010-1-3).

The BIONIX program (CANTIBio Inc, Seoul, Korea) was used to put together the various slices to obtain a 3D surface model (Figure 1a). For the convenience of the analysis, the right side of the mandible was deleted, and the finite element model of the left side of the mandible was obtained by the automesh technique of the BIONIX software (Figure 1b). The articular disc covering the condylar head was modeled by a fibrous cartilage band in biconcave shape with 2-mm, 1-mm, and 3-mm thickness at the anterior, middle, and the posterior area, respectively. As the force application area to the bone with bone-borne and hybrid type appliances, two titanium pins with 2-mm diameter were constructed in the cortical bone area close to the vertical osteotomy line. The final mesh consisted of 237,453 elements with 46,084 nodes. The mechanical properties of the materials18,19 are described in Table 1, and considered to be homogenous, isotropic, and linear elastic.

As the boundary conditions, the mandible was supported by restraining all the movements at the top of the articular disc, the buccal cusp, and fossa of the teeth. The jaw-closing muscles were supposed to generate on the centric occlusion as suggested by Korioth and Hannam<sup>18</sup> (Table 2). To simulate the expansion of the three types of distractors, expansion force was applied to the two titanium pins simultaneously with the bone-borne type distractor, to the first premolar and first molar with the tooth-borne distractor, and to the canine and the upper titanium pin with the hybrid appliance (tooth and bone-borne type), respectively. To visualize the definite differences of the effects of the three types of distractors, the expansion in each appliance was continued to 8 mm per side.



Figure 1. (a) Three-dimensional surface model of the mandible. (b) The finite element model of the left side of the mandible. The displacement and von Mises stress was measured at eight reference points (A, B, C, D, E, F, G, and H).

Table 1. Mechanical Properties of the Materials

| Material              | Young's Modulus, GPa | Poisson's Ratio |  |
|-----------------------|----------------------|-----------------|--|
| Cortical bone         | 13.6                 | 0.30            |  |
| Cancellous bone       | 0.378                | 0.30            |  |
| Fibrocartilage (disc) | 0.006                | 0.47            |  |
| Enamel                | 80.0                 | 0.30            |  |
| Dentin                | 17.6                 | 0.25            |  |
| Periodontal ligament  | 0.0027               | 0.45            |  |
| Titanium              | 110.0                | 0.33            |  |

The displacement and stress distribution at eight reference points illustrated in Figure 1b were measured. A color scale with eight stress values was used for quantitative visualization of the displacement and stress distribution of the mandible and articular disc.

#### RESULTS

### Displacement and Stress Distribution in the Mandible

Figure 2a through c shows the displacement of the mandible in each appliance. The lateral displacement

was decreased gradually from the anterior part to the posterior part, and the displacement at the ramus was hardly detectable especially in the bone-borne appliance. On the other hand, the tooth-borne appliance displaced the alveolar process and basal bone in a parallel manner from the incisor region to the premolar region with considerable displacement on the ramus. Vertically, the alveolar process area was displaced more than the basal bone area especially in the boneborne and the hybrid type (Figure 3; C < D, E < F, G < H). The displacements at eight reference points were larger in the tooth-borne appliance than the others, and smallest displacements were detected in the bone-borne appliance (Figure 3). The hybrid type showed a medium amount of displacement compared with the bone-borne and tooth-borne type.

Figure 2d through f shows the von Mises stress in the mandible. All distractors showed high stress concentration in the area adjacent to the appliance and the condylar neck area. The tooth-borne distractor appears to produce high level of the stress in the

 Table 2.
 Directions of Muscular Orthogonal Component Derived as Unit Vectors and Weighting and Scaling Factors Assigned to the

 Masticatory Muscles for Intercuspal Position

|                            | Unit Vectors (Left Side) |        |        |                     |                |
|----------------------------|--------------------------|--------|--------|---------------------|----------------|
| Masticatory Muscles        | COS-X                    | cos-y  | COS-Z  | Weighting Factor, N | Scaling Factor |
| Superficial masseter       | 0.207                    | 0.884  | 0.419  | 190.4               | 1.00           |
| Deep masseter              | 0.546                    | 0.758  | -0.358 | 81.6                | 1.00           |
| Medial pterygoid           | -0.486                   | 0.791  | 0.373  | 174.8               | 0.76           |
| Anterior temporalis        | 0.149                    | 0.988  | 0.044  | 158.0               | 0.98           |
| Middle temporalis          | 0.222                    | 0.837  | -0.500 | 95.6                | 0.96           |
| Posterior temporalis       | 0.208                    | 0.474  | -0.855 | 75.6                | 0.94           |
| Inferior lateral pterygoid | -0.630                   | -0.174 | 0.757  | 66.9                | 0.27           |



Figure 2. Displacement (a–c) and von Mises stress (d–f) of the mandible.



Figure 3. Displacement at eight reference points in the mandible.

alveolar process, mandibular body, and ramal region, while the bone-borne distractor showed low level of stress distribution. The hybrid type distractor showed more even stress distribution in the mandible than the others.

## Displacement and Stress Distribution in the Articular Disc

Figure 4 shows the displacement and stress distribution along the y-axis (anteroposterior direction) in the articular disc. The articular disc was displaced more in the anterolateral and posteromedial area of the disc (Figure 4a through c). The anteromedial and posterolateral area of the disc showed the compressive stress distribution, while the anterolateral and posteromedial area showed the tensile stress distribution (Figure 4d through f).

The maximum von Mises stress on the disc tended to increase with the amount of expansion (Table 3). The tooth-borne appliance showed highest stress levels in von Mises stress (Table 3), normal x-axis, y-axis, and z-axis stress, followed by hybrid appliance and bone-borne appliance (Figure 4 and Table 4).



Figure 4. Cross-sectional and bottom-up view for the displacement along the y-axis (a-c) and normal y-stress (d-f) of the articular disc. Positive values indicate more displacement and tensile stress (red color), while blue color means less displacement and compressive stress.

Table 3. Maximum von Mises Stress at the Articular Disc (MPa)

|             |       | Amount of Widening |       |       |       |  |  |
|-------------|-------|--------------------|-------|-------|-------|--|--|
| Distractors | 4 mm  | 5 mm               | 6 mm  | 7 mm  | 8 mm  |  |  |
| Bone-borne  | 47.2  | 57.2               | 67.1  | 77.0  | 86.9  |  |  |
| Tooth-borne | 124.0 | 155.0              | 186.0 | 217.0 | 248.0 |  |  |
| Hybrid type | 80.1  | 98.3               | 117.0 | 135.0 | 153.0 |  |  |

#### DISCUSSION

DO is a useful method for patients with severe craniomaxillofacial deformity to increase the amount of bony defect area. DO stimulates the growth of soft tissues including the muscles, the skin, and the hypodermal tissues, and thereby induces more esthetic results than conventional osteotomies,<sup>20,21</sup> and by allowing muscles and bones to adapt, the side effect on the TMJ is said to be smaller in comparison with orthognathic surgery.<sup>14</sup>

To predict the effects of DO, the distraction vector as well as various factors such as muscle force and the orientation or type of distractor should be considered because 3D movements and flexure of the mandible itself may occur during mastication. Gonzalez et al.22 mentioned the biomechanical effects of the medial pterygoid muscle in their animal study of simultaneous bilateral mandibular lengthening and midsymphyseal widening. However, there were a few FEA studies dealing with midsymphyseal DO that concerned the effect of the masticatory muscles in humans. Boccaccio et al.<sup>17</sup> considered the mastication force, but they only focused on the alveolar bone and the stability of the distraction appliance. In the present study, 3D finite element model was simulated under the jaw-closing muscle force exerted on the centric occlusion. Most of the jaw-closing muscles could generate the strongest force on the centric occlusion with the result that flexure of the mandible itself might occur and the direction of displacement could be changed. Boccaccio et al.<sup>17</sup> also reported that mastication produces parasite rotation effects on the mandible, thus reducing the overall displacement of the mandible.

The location and the orientation of the distractor is also important because it determines the shape of the new bone in the distraction gap.<sup>17,21,23</sup> There are

controversial opinions about the effects according to the type of distractors.9-11 Tae et al.11 reported that the tooth-borne distractor induced parallel expansion of the tooth and the bone and the hybrid distractor disproportional expansion. Our results are in agreement with the clinical findings of Tae et al.,<sup>11</sup> however in disagreement with the results of Del Santo et al.<sup>10</sup> that with a toothborne distractor the alveolar bone is expanded more than the basal bone, and King et al.<sup>9</sup> that the hybrid distractor induced balanced expansion. Biomechanically, if the expansion force is applied above the center of resistance of the mandible, the rotation of the bony segments might be expected, resulting in a disproportional widening between the tooth region and the basal bone region. However, the rotational effect of bony segments that arose by the mechanical expansion could also be compensated by masticatory muscle force.<sup>22</sup> Thus, it could also be estimated in a clinical situation that in the patient with strong masseter muscle or horizontal growth pattern, such compensation mechanism might be more remarkable. To which degree our findings were influenced by the masticatory forces can only be speculated.

Another issue is the effect of midsymphyseal DO on the TMJ. Clinically, degenerative changes of the TMJ caused by midsymphyseal DO seem to be a rare event.4,12,24,25 According to Samchukov et al.,13 however, mandibular widening induces rotation of the condyle about 0.34° per millimeter of midsymphyseal widening. Gökalp<sup>24</sup> also found 1° to 9° of posterolateral rotation of the condyle after symphyseal DO with toothborne appliance in the CT and MRI images. Braun et al.<sup>25</sup> investigated to determine the true nature of the condylar displacements in 12 patients treated with midsymphyseal DO (10 with tooth-borne and 2 with bone-borne type) and reported that each condyle was laterally displaced in direct relationship to the amount of symphyseal distraction, although there was no symptom associated with TMJ disorder. Harper et al.14 found the histologically altered area of the TMJ after midsymphyseal DO to the compressed area was caused by the rotation of the condyle around its vertical axis. These changes occurred in the posterior portion of the lateral third and the anterior portion of middle third and medial third of the condyle. In the

Table 4. Maximum Normal Stress at the Articular Disc With 8-mm Widening of the Distractors (MPa)<sup>a</sup>

|             | х       | x-axis      |         | y-axis      |         | z-axis      |  |
|-------------|---------|-------------|---------|-------------|---------|-------------|--|
| Distractors | Tensile | Compressive | Tensile | Compressive | Tensile | Compressive |  |
| Bone-borne  | 34.9    | -44.9       | 89      | -63.1       | 72.8    | -51.3       |  |
| Tooth-borne | 113     | -105        | 188     | -151        | 237     | -229        |  |
| Hybrid type | 69.5    | -99.6       | 138     | -100        | 147     | -125        |  |

<sup>a</sup> Positive values indicate tensile stress.

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present study the condyle was laterally displaced in all the distractors, although it was a minimal amount (Figure 2a through c), and the compressive stress was observed greatly on the anteromedial and the posterolateral area of the disc (Figure 4d through f).

These findings are in agreement with the results by Harper et al.<sup>14</sup> For maintaining the healthy state of TMJ the hard and soft tissues of TMJ should be able to accommodate the rotation and/or lateral displacements of the condyle and localized compressive stress on the disc after midsymphyseal DO. Gökalp<sup>24</sup> suggested that the rate and the rhythm of distraction are more important than the ultimate magnitude for allowing physiologic adaptation.

In comparison of distractor type, the tooth-borne distractor showed the highest stress levels in von Mises stress, normal x-axis, y-axis, and z-axis stress, followed by hybrid appliance and bone-borne appliance (Tables 3 and 4). These different effects among the distractors are probably caused by difference in the force application point. Bayram et al.<sup>26</sup> reported that the bone-borne distractor could produce a greater transverse increase in the anterior part of the mandible than in the posterior part. The clinical finding by Bayram et al.<sup>26</sup> is in accordance with our results (Figure 2a). More lateral displacement and excessive stress on the condyle and articular disc is to be expected in the toothborne appliance because it is seated in the more posterior region closer to the condyle than the hybrid and the bone-borne appliance. Whether any long-term side effects are anticipated, especially in tooth-borne distractor, remains to be investigated.

Although the FEA in this study does not reflect the tooth movement occurring from expansion force and bony resorption, it is thought to be not considerable. Because initial buccal displacement of teeth caused by a tooth-borne distractor is extremely small when the periodontal ligament is compressed, and the teeth and the mandible are expanded as a unit.25 In several studies, however, the displacement pattern of the teeth and the bony structures during the consolidation period of DO has been reported to be substantially different from the time immediately after the completion of midsymphyseal expansion.<sup>10,22,27</sup> This implies that after the displacement of bony segments, due to additional biomechanical actions, gradual adaptation to this change occurred in the dental arch. Hence, to simulate the difference of the mandibular changes immediately after expansion and after a certain period of bone consolidation, a complex factor such as occlusal force, the vector, and the force of the adjacent soft tissues including muscles from a new mandibular position must be considered. In addition, the limitation of FEA on biologic subjects is that when orthodontic forces are exerted, the resulting tooth movement cannot be reflected as in actual cases. Furthermore, as the model is based on the bone structure of a normal individual and not a micrognathic patient, the difference in the change of the mandibular complex has to be considered.

#### CONCLUSIONS

- The tooth-borne distractor produced more parallel bony widening in the midsymphyseal area and larger expansion in the molar region than the hybrid appliance and bone-borne appliance.
- The tooth-borne distractor, however, induced higher stress concentration on the articular disc than the hybrid appliance and bone-borne appliance.
- Whether any long-term side effects on TMJ are anticipated, especially in tooth-borne distractor, remains to be investigated.

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