Thin-plate Spline Analysis of the Effects of Face Mask Treatment in Children with Maxillary Retrognathism

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Background: Face mask therapy is indicated for growing patients who suffer from maxillary retrognathia. Most previous studies used conventional cephalometric analysis to evaluate the effects of face mask treatment. Cephalometric analysis has been shown to be insufficient for complex craniofacial configurations. The purpose of this study was to investigate changes in the craniofacial structure of children with maxillary retrognathism following face mask treatment by means of thin-plate spline analysis.  

Methods: Thirty children with skeletal Class III malocclusions who had been treated with face masks were compared with a group of 30 untreated gender-matched, age-matched, observation period-matched, and craniofacial configuration-matched subjects. Average geometries, scaled to an equivalent size, were generated by means of Procrustes analysis. Thin-plate spline analysis was then performed for localization of the shape changes.  

Results: Face mask treatment induced a forward displacement of the maxilla, a counterclockwise rotation of the palatal plane, a horizontal compression of the anterior border of the symphysis and the condylar region, and a downward deformation of the menton. The cranial base exhibited a counterclockwise deformation as a whole.  

Conclusion: We conclude that thin-plate spline analysis is a valuable supplement to conventional cephalometric analysis. [J Formos Med Assoc 2006;105(2):147–154]  

Key Words: face mask, malocclusion angle class III, maxilla, retrognathism

Class III malocclusion is one of the most difficult facial deformities to manage because of the great diversity in anatomic craniofacial structures and the unpredictable growth in patients with this skeletal pattern. While a relatively high prevalence of Class III malocclusion has been observed in Asian children,¹–⁴ studies assessing the effects of orthopedic treatment have been limited. Maxillary retrusion was reported as a component of skeletal Class III malocclusion in 42–63% of patients.⁵–¹¹ For a growing patient who suffers from maxillary retrognathia with or without mild mandibular prognathism, maxillary protraction with a face mask is an adequate method of treatment. Maxillary protraction therapy is sometimes combined with palatal expansion in the belief that palatal expansion may disrupt the circummaxillary suture system and, thus, enhance the protraction effect of the face mask.¹²

Several previous studies found that the clinical effects of maxillary protraction include forward and downward movement of the maxillary bone and dentition, set back of the menton, mandibular downward and backward movement, lingual in-
clination of the mandibular incisors, and augmentation of the facial height.\textsuperscript{13–17} However, the conventional roentgenographic cephalometric analysis used in these studies has certain limitations. Measurement of lines and angles by traditional methods is not able to locate the actual sites where growth or treatment changes have occurred within the craniofacial skeleton. The conventional metric approach has to depend on reference planes and points. If the registration points or planes vary greatly, the use of such techniques may cause misdiagnosis or misinterpretation.\textsuperscript{18,19}

Recently, newer geometric morphometric methods for shape comparisons have been developed to measure the biologic size and shape changes induced by growth and treatment.\textsuperscript{20–23} These methods are preferable to conventional cephalometry in that they provide explanatory visualization of shape changes and highlight regions of localized dissimilarity. Among these methods, thin-plate spline analysis was introduced by Bookstein in 1989.\textsuperscript{24} Thin-plate analysis expresses the difference between two configurations with transformation grids and models the continuous deformation of one form to another using regression functions.

Most previous studies evaluated the treatment effects of face mask therapy using conventional roentgenographic cephalometric analysis. As mentioned above, conventional cephalometry is insufficient for the analysis of complex craniofacial configurations. The purpose of this study was to use thin-plate spline analysis to investigate the changes in the craniofacial structure of children after face mask treatment for maxillary deficiency.

**Methods**

**Study sample**
The treatment group consisted of 30 subjects (15 males, 15 females; mean age, 9.04 years; age range, 5.3–12.3 years; mean treatment period, 9.5 months) who were treated with face masks in the Department of Orthodontics, National Taiwan University Hospital. Patients were selected on the basis of the following inclusion criteria: Chinese ancestry; lateral cephalograms of adequate quality available at the beginning and end of treatment; hand wrist film showing skeletal growth potential at the time of the start of treatment; diagnosis of maxillary deficiency; no cleft lip, cleft palate or any other craniofacial deformities; Wits appraisal of $< -3.5$ mm and ANB angle (A point-nasion-B point angle) between $0^\circ$ and $2^\circ$ or $< 0^\circ$; no congenitally missing or extraction of permanent teeth before or during treatment; and the patient had been treated with a face mask.

Thirty subjects with untreated Class III malocclusion were selected from the department’s files to make up the control group. They were selected to match with the individual members of the treatment group by race, gender, age at the start of observation, duration of the observation period, and craniofacial configuration. The control group comprised 30 subjects (15 males, 15 females; mean age, 9.03 years; age range, 5.8–12.0 years; mean observation period, 9.4 months).

Direct evaluation of the treatment effect by comparing the differences between the treatment and control groups, without the need for annualizing the data, was feasible because the two groups were so well matched.

**Treatment regimen**
Patients in the treatment group were treated with Petit-type face masks with pads fitted to the chin and forehead for support. Elastics were worn from the intraoral attachments to the support bar of the face mask. The force vector was directed slightly downward and forward, producing an orthopedic force of 300–600 g on each side. Patients were instructed to wear the face mask for more than 12 hours a day. Palatal expansion was indicated for patients with a constricted maxilla. The amount of transverse change was considered desirable when the lingual cusps of the upper posterior teeth approximated the buccal cusps of the lower posterior teeth.

**Digitization of craniofacial landmarks**
Lateral cephalograms were traced with a 0.3-mm lead pencil on frosted acetate tracing films in
random order and checked by one investigator. Twenty-two homologous craniofacial landmarks were identified and digitized (Figure 1). Landmarks were selected, with preference given to those that encompassed developmental sites, were easily distinguishable, and were located in the midsagittal plane where possible. All cephalograms were retraced after a 1-week interval and the landmarks were redigitized by the same person. None of the landmarks showed a discrepancy > 1% for each x and y coordinate on duplicate digitization. Thus, errors of identification were neglected.

**Procrustes superimposition and statistical estimation**

The scaled mean craniofacial configurations for the treatment and control groups at the beginning of treatment (T1) and end of treatment (T2) were generated with the Procrustes analysis. Procrustes analysis was performed using the least-squares principle to translate, rotate, and iteratively scale every subject’s coordinates until all configurations could no longer be improved by the least-squares fit. These mean forms were tested for statistical significance using Goodall’s F test. Residuals and corresponding F values were computed, tabulated and compared.

**Thin-plate spline analysis**

The scaled mean craniofacial configurations generated with the Procrustes analysis were subjected to thin-plate spline analysis using the tpsSpline program. The shape changes between T1 and T2 for both groups as well as the differences between the treatment and control groups at T2 were graphically displayed in transformation grids. These changes in craniofacial configurations were interpreted visually.

**Results**

**Distribution of residuals**

Residuals from Procrustes analysis were tabulated and compared by means of an F distribution (Table). No significant differences could be found between the treatment group at the start of treatment (TxT1) and the control group at the beginning of the observation period (CtrlT1) (p > 0.5), indicating that the craniofacial configurations of these two groups were well matched at the beginning of treatment. Significant differences were found between mean pretreatment and mean post-treatment craniofacial configurations (TxT1 – TxT2) (p < 0.001). The mean configurations of the control group were also significantly different between the beginning and end of the observation period (CtrlT1 – CtrlT2) (p < 0.001), implying that the craniofacial configurations of both the treatment and control groups changed with time. Significant differences were also found in the craniofacial configurations between the treatment group at the end of treatment and the control group at the end of the observation period (CtrlT2 – TxT2) (p < 0.001), indicating that face mask treatment induced significant changes in craniofacial configuration. These significant changes enabled further graphic analysis with the thin-plate spline to be carried out.

<table>
<thead>
<tr>
<th>Group</th>
<th>Residual</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CtrlT1 – TxT1</td>
<td>0.000077405</td>
<td>0.8209</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>CtrlT1 – CtrlT2</td>
<td>0.000078891</td>
<td>4.0824</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>TxT1 – TxT2</td>
<td>0.00003007</td>
<td>4.2990</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>CtrlT2 – TxT2</td>
<td>0.000037575</td>
<td>4.0312</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

*T1 = start of treatment; T2 = end of treatment.*
**Thin-plate spline analysis of shape changes during face mask treatment**

Figure 2A shows the mean craniofacial configuration derived from the 30 treatment subjects before face mask treatment (T1) in untransformed space. Figure 2B shows the pattern of deformation of the mean grid of these 30 subjects after transformation into the mean morphology derived after face mask treatment (from T1 to T2). The transformation grid showed evidence of a forward extension in the maxillary region along the PNS (posterior nasal spine) to MPP (midpalatal point) horizontal axis. Anterior displacement was evident at points ANS (anterior nasal spine), A (position of deepest concavity on anterior profile of the maxilla) and Pr (prosthion). There was a horizontal compression in the region of the anterior border of the mandibular symphysis, especially at point B (position of deepest concavity on anterior profile of the mandibular symphysis).

**Thin-plate spline analysis of shape changes in the control group during the observation period**

Figure 3A shows the mean craniofacial configuration derived from the 30 control subjects at the beginning of the observation period (T1) in untransformed space. Figure 3B shows the pattern of deformation of the mean grid of these 30 control subjects after transformation into the mean morphology derived after the observation period (from T1 to T2). The transformation grid revealed a slight horizontal compression in the anterior region of the maxilla, especially at point A. The anteroinferior border of the mandibular symphysis exhibited forward extension, mostly at point Pog (pogonion).

**Effects of face mask therapy**

Since the control subjects were well matched to treated subjects, direct comparison of the differences between the two groups to reveal the pure treatment effects of face mask therapy was possible (Figure 4). The transformation grid showed an obvious anterior forward extension of the maxilla along the PNS-MPP horizontal axis. Point PNS was displaced anteriorly relative to point PtmS (pterygomaxillary fissure superior). Points ANS, A and Pr showed significant forward displacement. A slight downward deformation of point PNS and an upward deformation of point ANS caused the counterclockwise rotation of the palatal plane.

A forward compression was noted at the mandibular condylar region near point Ar (articulare). The anterior border of the mandibular symphysis exhibited some horizontal compression. A downward deformation of point Me (menton) was also evident. The overall mandibular configuration had a clockwise deformation.
There was a forward extension of the anterior cranial base which was evident at Rh (rhinion). A downward and forward deformation of the sphenoidal complex and the sphen-o-occipital synchondrosis region was also noted. The cranial base exhibited a counterclockwise deformation as a whole.

Discussion

Geometric morphometric analysis is superior to conventional cephalometry in that no conventional reference lines are required, an explanatory visualization of morphologic differences is provided, and the actual sites where the size and shape changes occurred are localized.18,19 Although registration-free, morphometric techniques are not coordinate-free; these techniques still depend on landmark selection.28 Selection of landmarks and interpretation of results must be treated with caution because thin-plate spline interpolation does not take account of the biologic structure, but computes based on the location of the landmarks. The intermediate points are considered homologous.29 Therefore, we preferred to select landmarks that encompassed developmental sites and those that were located in the midsagittal plane where possible; accurate digitization of the landmarks was also important.

Several morphometric approaches have been proposed in the last two decades. Each technique has its relative merits and is able to provide certain types of information. Among these methods, thin-plate spline analysis was introduced to express the differences of two forms as a continuous deformation by visualizing biorthogonal grids.24 This approach has gained increasing popularity. Spoor et al previously employed thin-plate spline analysis in the examination of anterior sphenoid in modern humans.30 Singh et al described the cranial base configurations and the characteristics of soft-tissue profiles in individuals with Class III malocclusion.31–33 Bookstein identified congenital midfacial deformities in patients with Apert’s syndrome using thin-plate spline analysis.20 Pae et al investigated the shape characteristics of the face and tongue in patients with obstructive sleep apnea using thin-plate splines.34 Franchi et al demonstrated the usefulness of thin-plate spline analysis in describing mandibular growth.35 Yaroch used thin-plate spline analysis to investigate Neanderthal cranial shape.36 Thin-plate spline analysis has provided a valuable supplement to conventional cephalometric analysis because of its efficiency in describing the shape variations during craniofacial growth and in comparing the morphologic differences between two biologic forms.

Thin-plate spline analysis allows the visualization of differences between two mean configurations as a grid regardless of whether these differences are significant or not. Thus, prior to thin-plate spline examination, the mean configurations of the treatment and control groups should be analyzed for statistical significance. In this study, to determine whether these mean craniofacial configurations were morphologically different, we relied on the residuals of homologous landmarks obtained by Goodall’s F test. The statistical results indicate that the craniofacial configurations of both the treatment and control groups changed with time and that face mask treatment induced significant changes in craniofacial configuration. These significant changes enabled further geometric and graphic analyses with the thin-plate spline to be carried out.
Our search of the literature revealed only two previous studies that employed the newer geometric morphometric analyses in the examination of face mask treatment effects in patients with Class III malocclusions, both by the same group of researchers. The first study, reported in 1998 by Franchi et al, evaluated the shape and size changes of the maxilla and mandible in children with Class III malocclusion treated with face mask combined with rapid maxillary expansion using shape-coordinate and tensor analyses. The treatment samples were divided into two subgroups: the early-treated group and the late-treated group. Their study concluded that treatment in early mixed dentition was more effective than in late mixed dentition. In 1999, the same group of researchers used thin-plate spline analysis to investigate the shape changes in the craniofacial configurations of the early-treated group. They concluded that face mask combined with rapid maxillary expansion induced a forward displacement of the maxilla, a counterclockwise rotation of the palatal plane, a forward compression of the mandibular condylar region, and a compression in the region of the anterior surface of the mandibular symphysis. One major problem of the first study, which employed shape-coordinate and tensor analyses, was that the researchers investigated the maxillary configuration as a large maxillary triangle that was constructed with the points T (tuberculum sellae), FMN (frontomaxillonasal suture) and A; and the mandibular configuration as a large mandibular triangle that was constructed with the points Co (condylion), Go (gonion) and Pog. The poverty of accepted landmarks used in their study led to the generation of too few triangular elements, and the large element size employed failed to reflect detailed local differences. In their second study, thin-plate spline analysis modeled biologic shape differences as a continuous deformation analogous to the bending of an infinitely thin metal plate, which allowed localization of the actual sites where the size and shape changes occurred. However, in that study, the control subjects were not individually matched to the treated subjects; thus, their conclusion was limited to describing the shape changes during the treatment period, which were due to a combination of the treatment effects plus the changes caused by growth. In the present study, the control subjects were individually matched to the treated subjects with regard to race, gender, age at the start of observation, duration of the observation period, and craniofacial configuration. Statistical analysis verified the similarity of the craniofacial configurations of the two groups prior to treatment. This limited the confounding effects of factors not related to face mask treatment.

Our results showed that orthopedic treatment using a face mask in patients with Class III malocclusion not only affected the midfacial region, but also influenced the mandibular and cranial base areas. The transformation grid showed a forward advancement of the maxilla, a horizontal compression of the anterior border of the mandibular symphysis, and a downward deformation of point Me. These results concur with the findings of the clinical effects of maxillary protraction using conventional cephalometric analysis. A slight downward deformation of point PNS and an upward deformation of point ANS also explained the counterclockwise rotation of the palatal plane as seen in clinical situations. Although conventional cephalometric analysis indicated that the mandible rotated downward and backward after face mask treatment, it could not locate the actual sites where the changes occurred. In contrast, thin-plate spline analysis revealed a forward compression at the mandibular condylar region near point Ar and an overall clockwise deformation of the mandibular configuration. Most conventional studies failed to detect any changes in the cranial base region during face mask treatment. However, this study demonstrated a forward extension of the anterior cranial base and a downward and forward deformation of the sphenoidal complex and sphenoid-occipital synchondrosis region. These findings are in agreement with results of animal experiments that transmission of extraoral forces through the maxilla resulted in changes in deep cranial structures, such as the spheno-occipital and midsphenoidal synchondroses.
This study hypothesized that thin-plate spline analysis could express the shape changes in craniofacial configuration after face mask therapy. Although we could not demonstrate that the results reflected biologic responses, our findings are in agreement with those obtained by conventional cephalometric techniques and could be related to the findings of animal studies. Our results indicate that thin-plate spline analysis is a valuable supplement to conventional cephalometric analyses.

This study had several limitations in addition to its retrospective design. Multiple factors such as differences in intra-oral appliances, magnitude of traction forces, direction of forces, severity of craniofacial deformity, patient compliance, and growth potential are potential confounding variables that might have influenced the results of this study. A carefully conducted prospective randomized clinical trial would be of value in establishing the effects of face mask therapy. Further studies based on finite element morphometry will enable both localization and quantification of allometry within the midfacial, mandibular and cranial base regions. Future studies may comprise the analysis of three-dimensional data in a prospective randomized clinical trial.

We conclude that thin-plate spline analysis can localize the exact shape changes in craniofacial configuration after orthopedic treatment and is, therefore, a valuable supplement to conventional cephalometric analysis.

References

24. Bookstein FL. Principal warps: thin-plate splines and the


