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Thin-plate spline analysis of the short- and long-term effects of rapid maxillary expansion

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SUMMARY The aim of this study was to investigate the short- and long-term effects induced by rapid maxillary expansion (RME) on the shape of the maxillary and circummaxillary structures by means of thin-plate spline (TPS) analysis. The sample consisted of 42 patients who were compared with a control sample of 20 subjects. The treated subjects underwent Haas-type RME, followed by fixed appliance therapy. Postero-anterior (PA) cephalograms were analysed for each treated subject at T_1 (pre-treatment), T_2 (immediate post-expansion), and T_3 (long-term observation), and were available at T_1 and T_3 for the control group (CG). The mean age at T_1 was 11 years and 10 months for both groups. The mean chronological ages at T_3 were 20 years, 6 months for the treated group (TG) and 17 years, 8 months for the control group. The study focused on shape changes in the maxillary, nasal, zygomatic, and orbital regions.

TPS analysis revealed significant shape changes in the TG. They consisted of an upward and lateral displacement of the two halves of the naso-maxillary complex as a result of active expansion in the short-term, and normalization of maxillary shape in the transverse dimension in the long-term (the initial transverse deficiency of the maxilla in the treated group was eliminated by RME therapy both in the short- and long-term). At the end of the observation period, the nasal cavities were larger when compared with both their pre-expansion configuration and the final configuration in the controls. RME with the Haas appliance appears to be an efficient therapeutic means to induce permanent favourable changes in the shape of the naso-maxillary complex.

Introduction

Rapid maxillary expansion (RME) has gained increasing popularity in contemporary dentofacial orthopaedics. The main objectives of the technique aimed at widening the maxilla include the following:

1. correction of posterior crossbites (Haberson and Myers, 1978; Hesse *et al.*, 1997);
2. increase of supplementary arch perimeter to accommodate teeth in patients with tooth size–arch size discrepancies (Adkins *et al.*, 1990; McNamara and Brudon, 1993);
3. activation of the circummaxillary sutural system in treatment protocols for Class III malocclusions involving maxillary expansion and protraction (McNamara and Brudon, 1993; Baccetti *et al.*, 1998);
4. elimination of inter-arch transverse discrepancies prior to orthopaedic intervention in Class II malocclusions (Tollaro *et al.*, 1996; Baccetti *et al.*, 1998).

From a clinical perspective, the main outcome of RME is an increase in the transverse dimension of the maxillary arch. Skeletal modifications throughout the naso-maxillary complex also contribute to the end result. Investigations of postero-anterior (PA) cephalograms appear to be ideal for the evaluation of possible skeletal changes associated with RME therapy. To date, however, the numbers of studies that have been conducted on PA cephalograms are limited and they have seldom taken into consideration the long-term outcomes of RME (Thörne, 1956; Haas, 1961, 1970, 1980; Krebs, 1964; Davis and Kronman, 1969; Wertz, 1970; Wertz and Dreskin, 1977; Herberger, 1987; Berger *et al*., 1998).

A valid option for the analysis of craniofacial skeletal changes due to growth and/or to treatment is represented by descriptive methods of shape and shape change that have been developed and implemented as major improvements when compared with conventional cephalometrics (Blum, 1973; Bookstein, 1982, 1991; Lestrel, 1982; Cheverud *et al.*, 1983; Lavelle, 1985; Lestrel and Roche, 1986; Dryden and Mardia, 1998). In particular, Bookstein's morphometric innovations [tensor, shape-coordinate, thin-plate spline (TPS) analysis] have been used to investigate modifications in shape related to functional or orthopaedic treatment of facial skeletal imbalances in the sagittal plane (McNamara *et al*., 1985; Kerr and TenHave, 1988; Ngan *et al*., 1993; Battagel, 1994; Baccetti and Franchi, 1997; Singh *et al*., 1997; Franchi *et al*., 1998; Baccetti *et al*., 1999).

The aim of the present investigation was to evaluate craniofacial short- and long-term modifications induced by RME therapy by means of TPS analysis applied to PA cephalograms. This analysis will provide a description of the deformations occurring in the maxillary, zygomatic, nasal, and orbital regions as a result of RME.

Subjects and methods

Treated group (TG)

A sample of 42 subjects (25 females, 17 males) treated with Haas-type RME and non-extraction edgewise appliance therapy in a single orthodontic practice were investigated. The records included pre-treatment (T_1), immediate post-RME screw fixation (T_2), and post-treatment (minimum 5 years after all fixed appliances were removed; T_3) PA cephalograms. The PA cephalograms were taken according to a standardized technique, similar in principle to that used by Broadbent (1931).

The patients originally presented with transverse maxillary deficiency as part of their overall orthodontic problem. Haas-type RME was performed with two turns a day (0.25 mm per turn) until the expansion screw reached 10.5 mm (about 21 days). The Haas expander was used on the maxillary dentition as a passive retainer for an average period of two months (average = 65 days; range = 42–75 days). Immediately after removal of the Haas expander, fixed standard edgewise appliances were inserted.

Control group (CG)

Twenty subjects (11 males and nine females) who did not undergo orthodontic treatment were selected from the records of the University of Michigan Elementary and Secondary School Growth Study (Riolo *et al*., 1974). The treated and control groups were matched with regard to chronological age. The mean age at T_1 was 11 years and 10 months for both the treated and the control groups. The mean chronological ages at T_3 were also comparable (20 years, 6 months for the TG and 17 years, 8 months for the CG). It is important to note that because no sexual differences were found for all PA cephalometric variables in previous studies (Wertz, 1970; Athanasiou *et al*., 1992; Sandikcioglu and Hazar, 1997), the present sample was not separated according to sex. All individuals in both the treatment and control groups were Caucasian.

Cephalometric analysis

Serial PA cephalograms were hand-traced using a 0.5-mm lead pencil on 0.003-mm matte acetate tracing paper. All tracings were performed by one investigator and subsequently verified by another investigator. The traced PA cephalograms were analysed by means of a digitizing tablet (Numonics, Landsdale, Pennsylvania, USA) and digitizing software (DFP Plus 2.02, Dentofacial Software, Toronto, Ontario, Canada).

Figure 1 shows the skeletal and alveolar landmarks used in the PA tracings. Magnification was 9.0 per cent in the TG and 12.92 per cent

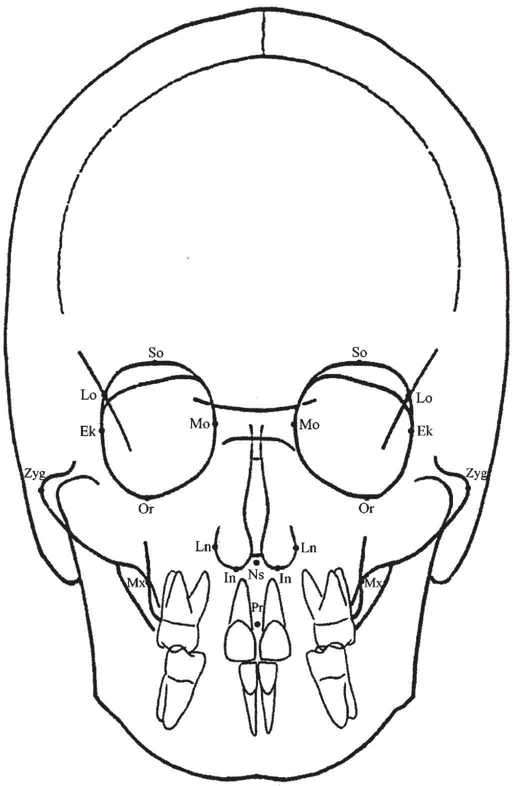

Figure 1 Craniofacial landmarks used in the study.

in the CG. All cephalograms were converted to a 9.0 per cent enlargement.

The following bilateral cephalometric landmarks in the maxillary, zygomatic, nasal, and orbital regions, with their corresponding definitions, were used:

1. Medio-orbitale (Mo)—the most medial point of the orbital orifice.
2. Orbitale (Or)—the lowest point of the orbital orifice.
3. Ectoconchion (Ek)—the most lateral point of the orbital contour.
4. Latero-orbitale (Lo)—the intersection of the lateral wall of the orbit and the greater wing of the sphenoid (the oblique line).
5. Supra-orbitale (So)—the highest point of the orbital orifice.
6. Zygomatic (Zyg)—the most lateral point of the zygomatic arch.
7. Maxillare (Mx)—the point located at the depth of the concavity of the right lateral maxillary contour, at the junction of the maxilla and the zygomatic buttress.
8. Lateronasal (Ln)—the most lateral point of the nasal cavity.
9. Inferonasal (In)—the most inferior point of the nasal cavity.

In addition, the following midline points were included in the analysis:

10. Nasal septum (Ns)—the point located at the intersection of the nasal septum with the floor of the nose.
11. Prosthion (Pr)—the tip of the alveolar crest between the maxillary central incisors.

To analyse the combined error of landmark location, tracing, and digitization, 10 randomly selected PA cephalograms were retraced and redigitized. The standard error deviation for each dimension was calculated from the double determinations using Dahlberg's formula. For the measurements used, the mean value of the method error was 0.7 ± 0.3 mm.

TPS analysis

TPS analysis offers a quantitative appraisal of the spatial organization of differences in shape change (Swiderski, 1993). In TPS analysis, the differences in two configurations of landmarks are expressed as a continuous deformation using regression functions in which homologous points are matched between forms to minimize the bending energy (Richtsmeier *et al.*, 1992). 'Bending energy' can be defined as the energy that would be required to bend an infinitely-thin metal plate over one set of landmarks so that the height over each landmark is equal to the co-ordinates of the homologous point in the other form (Rohlf and Marcus, 1993). TPS analysis enables the construction of transformation grids that capture the differences in shape and are available for visual interpretation. For a review of theoretical bases and calculation procedures related to TPS morphometrics, see Bookstein (1991), Rohlf and Marcus (1993), Rohlf *et al*. (1996), and Dryden and Mardia (1998).

In the present study, the TPS program (tpsRegr V. 1.19 by F. James Rohlf, Department of Ecology and Evolution, SUNY at Stony Brook, 1998) computed the orthogonal least-squares Procrustes average configuration of landmarks at all observation times in the treated group (T_1, T_2, T_3) and in the control group (T_1, T_3). It is important to point out that the time interval between T_1 and T_2 for the treatment group did not exceed 30 days, which virtually eliminates growth as a variable. Therefore, for comparison purposes, it was assumed that the measurements for the control group at T_2 coincided with the measurements of the control group at T_1.

The average craniofacial configurations were subjected to TPS analysis to make comparisons on differences in shape both within the treated group (TG), and between the TG and the control group (CG) at subsequent observation times:

1. TG at T_1 versus CG at T_1.
2. TG at T_1 versus TG at T_2.
3. TG at T_1 versus TG at T_3.
4. TG at T_2 versus CG at T_1.
5. TG at T_3 versus CG at T_3.

Statistical analysis of shape differences was performed by means of permutation tests with 1000 random permutations on Wilks' Lambda statistics. Permutation tests were carried out as most landmarks slide along curves when shape changes are analysed.

Results

Shape differences between TG and CG at T_1 (Figure 2)

The maxilla was significantly narrower ($P = 0.003$) in the TG when compared with CG before treatment. This was due to compression in the horizontal plane at point Mx bilaterally. The difference was associated with compression of the midface in the vertical plane because of a downward displacement of point Or bilaterally. A vertical extension of the lateral portions of the face in an upward direction was also detectable as a consequence of an upward displacement of point Zyg bilaterally.

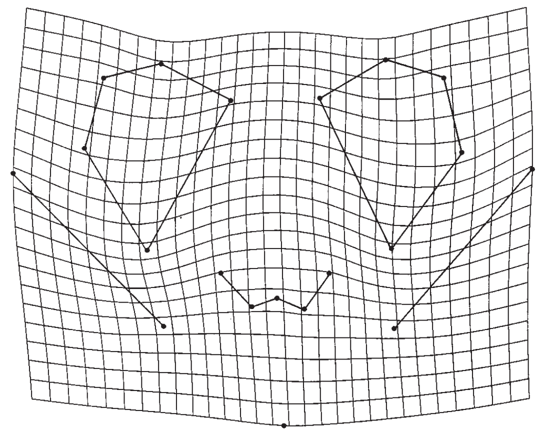

Figure 2 Thin-plate spline graphical display for the shape differences between the treated and control groups at T_1 (magnification factor ×4).

Shape changes in the TG from T_1 to T_2 (Figure 3)

The active phase of treatment with RME induced significant changes ($P = 0.003$) in the shape of the maxillary and nasal regions. The greatest deformation could be described as a widening of the maxilla and of the base of the nose, i.e. a bilateral extension in the horizontal plane that was due to a lateral displacement of points Ln, In, and Mx. A vertical extension in an upward direction was also detectable as the

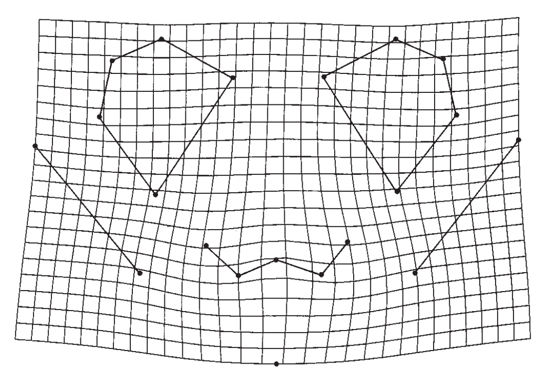

Figure 3 Thin-plate spline graphical display for the shape changes in the treated group from T_1 to T_2 (magnification factor ×4).

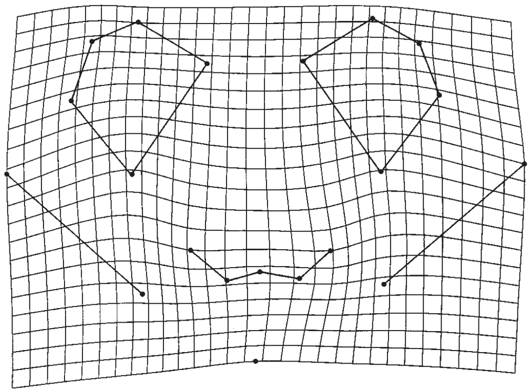

Figure 4 Thin-plate spline graphical display for the shape changes in the treated group from T_1 to T_3 (magnification factor ×4).

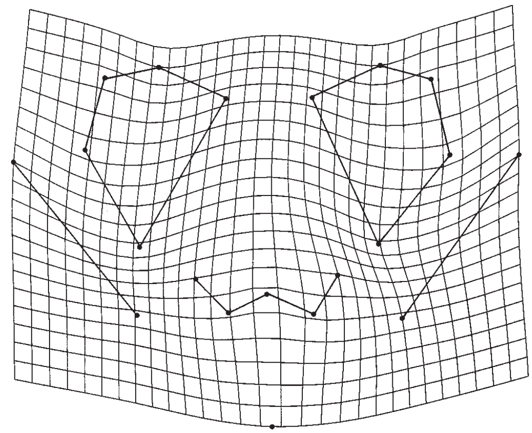

Figure 5 Thin-plate spline graphical display for the shape differences between the treated and control groups at T_2 (magnification factor ×4).

result of an upward displacement of point Zyg bilaterally.

Shape changes in the TG from T_1 to T_3 (Figure 4)

Modifications in shape in the long-term still included a widening of the nasal base. Significant changes in the overall observation period for the TG ($P = 0.001$) consisted mainly of a bilateral horizontal extension in the nasal region. This was associated with a downward displacement of point Zyg bilaterally and with an upward displacement of the orbital points bilaterally.

Shape differences between the TG and CG at T_2 and T_3 (Figures 5 and 6)

Treatment with RME induced significant alterations in the naso-maxillary complex in the transverse plane. A permanent enlargement of the base of the nose was achieved as revealed by the significant bilateral extension in the horizontal plane of the nasal region ($P < 0.01$) in the TG. The initial transverse deficiency of the maxilla in the TG was eliminated by RME therapy both in the short- and long-term. The position of point Mx did not show any difference in the TG when compared with the controls at both T_2 and T_3. A horizontal extension of the nasal area in TG could be detected at T_3. The initial shape differences in the orbital and zygomatic areas persisted at T_2 and T_3.

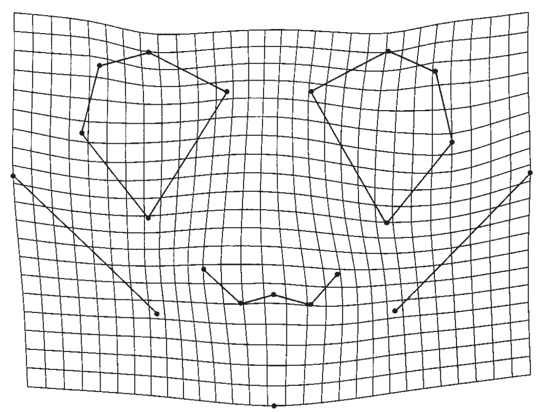

Figure 6 Thin-plate spline graphical display for the shape differences between the treated and control groups at T_3 (magnification factor ×4).

Discussion

The aim of the present work was to analyse treatment and long-term post-treatment effects of RME in growing subjects. The analysis was performed with the aid of a morphometric method for the description of shape changes in the craniofacial region and with emphasis on modifications occurring in the maxillary, nasal, zygomatic, and orbital areas.

Specifically, this investigation consisted of:

1. appraisal of shape changes in the frontal plane by applying TPS analysis to PA cephalograms;
2. use of a CG for the evaluation of differences in morphological characteristics between treated and untreated subjects at different time intervals;
3. analysis of morphological craniofacial adaptations in the long-term after completion of a standardized treatment protocol consisting of RME and fixed appliance therapy.

There are major advantages with regard to the application of TPS analysis to cephalometric landmark configurations when compared with both conventional cephalometrics and previous morphometric tools (tensor and shape-coordinate analyses). These advantages include: (1) an optimal superimposition of landmarks for the analysis of shape change in complex skeletal configurations without the use of conventional reference lines; and (2) an explanatory visualization of the deformations due to growth and/or treatment using transformation grids.

With respect to the controls, the initial morphological characteristics of the treated sample consisted mainly of compression of the maxilla in both the transverse and vertical planes (Figure 2). RME therapy is able to expand the maxilla sufficiently to eliminate the maxillary compression completely in the horizontal plane and to induce an enlargement of the inferior portion of the nasal cavities in the short-term (Figures 3 and 5). The findings of the present study indicate that RME induces morphological changes in the naso-maxillary complex that can be described as a displacement of the two halves of the mid-facial structures in an outward and upward direction. The fulcrum of the bilateral displacement appears to be located between the medial ridges of the two orbits (Figure 3). These observations agree with the results of previous studies regarding the outcome of RME on the craniofacial skeleton performed with the aid of implants (Krebs, 1958), on human dry skulls (Wertz, 1970), and on non-human primates (Cleall *et al*., 1965). The outcome is typified by the maxilla separating into a triangular shape when viewed in the frontal plane with the base of the triangle near the upper central incisors and the apex in the fronto-nasal area.

Consideration was also given to the morphological features of the TG in the long-term. Comparisons were made with both the pre-expansion configuration of the treated subjects and with the long-term configuration of the controls. The results displayed a normalization in the shape of the maxilla in the transverse plane and a net enlargement of the inferior portion of the nasal cavities (Figures 4 and 6). Moreover, the TG exhibited an enlargement of the maxillary complex in the vertical plane due mainly to an upward displacement of the orbits (Figure 4). The shape change in the vertical dimension of the maxilla in the treated sample was most likely the result of growth changes involving both bone remodelling and enlargement of the maxillary sinuses.

The few cephalometric investigations of the long-term craniofacial adaptations to RME therapy with the Haas expander report variable outcomes with regard to the stability of maxillary expansion (Krebs, 1964; Haas, 1980; Herberger, 1987). None of these studies, however, incorporated a CG of untreated subjects. The results of the present morphometric research on the long-term effects of RME demonstrate that the shape of the maxilla in the transverse plane is normalized with respect to controls after an average time period of eight years after expansion. The treatment-induced enlargement of the nasal cavities is maintained throughout the post-expansion period.

Conclusions

RME is an effective therapeutic procedure to induce significantly favourable morphological changes in the craniofacial region. The shape modification consists of the displacement of the two halves of the naso-maxillary complex in an outward and upward direction. The fulcrum of the bilateral displacement appears to be located between the medial ridges of the two orbits.

RME therapy is able to normalize the shape of the maxillary complex in the long-term.

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