Effect of biomechanical disturbance of the temporomandibular joint on the prevalence of internal derangement in mandibular asymmetry

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SUMMARY The aim of the present study was to elucidate the relationship between biomechanical changes of the temporomandibular joint (TMJ) and internal derangement (ID) symptoms in mandibular asymmetry. Posteroanterior cephalograms (PA) of 140 patients with TMJ ID associated with mandibular asymmetry were used to investigate the inclination of the frontal occlusal plane (FOP), and were analysed in conjunction with the results of a report providing information on ID symptoms. A three-dimensional (3D) finite element model (FEM) of the entire mandible was created to investigate the distribution of TMJ forces during clenching. The inclination of the FOP was modified to simulate various degrees of vertical asymmetry. The stresses on the TMJ on the ipsilateral and contralateral sides were analysed and their values were compared with those of the standard model.

The results showed that the symptomatic sides were significantly related to the degree of inclination of the FOP. Increasing its angulation resulted in a decrease of the symptoms on the ipsilateral side and an increase of those on the contralateral side. The analysis showed that stress-distribution patterns and overall stresses of the articular disc were influenced by the angulation of inclination of the FOP. These mechanical changes exhibited a distinct relationship with the prevalence of ID in the patients. These results suggest that disturbances in the stresses either in amount or direction due to occlusal inclination can be responsible for ID. Therefore, an attempt to establish a flat occlusal plane is an important orthodontic treatment objective in maintaining the normal health and structure of the TMJ.

Introduction

Internal derangement (i.e. disc displacement) is the most common cause of temporomandibular disorders defined as localized mechanical disorders interfering with smooth joint movement. A high incidence of temporomandibular joint internal derangement (TMJ ID) associated with mandibular asymmetry patients has been reported (Katzberg et al., 1985; Kurihara et al., 1996, Fushima et al., 1999). A previous study has revealed that vertical asymmetry of the mandible, such as the inclination of the frontal occlusal plane (FOP) and the inclination of the frontal mandibular plane (FMP), is related to TMJ ID (Trpkova et al., 2000). However, there is no information on how vertical asymmetry affects the TMJ and leads to TMJ ID. Biomechanically, these structural disturbances may affect the mechanical stress that occurs within the TMJ. These disturbances might play a role in the development of TMJ ID.

Stresses in the TMJ are considered to be important for maintaining normal structure and function of the TMJ (Mow and Mak, 1988) and of all other related components in the stomatognathic system. The belief that inappropriate mechanical loading of the TMJ results in joint dysfunction is sustained in the biomechanical study of the TMJ.

In spite of the difficulties inherent in directly measuring the stresses in the human TMJ, finite element models (FEMs) have been developed and successfully used for clarifying TMJ biomechanics. Haskell et al. (1986) and Maeda et al. (1991) developed two-dimensional FEMs of the mandible to investigate stress distribution in the TMJ. Three-dimensional (3D) models were subsequently developed to more accurately simulate the human mandible, including the TMJ (Korioth and Hannam, 1994; Tanaka et al., 1994; Nagahara et al., 1999). Some of these models were used to investigate the influences of craniofacial discrepancy (Tanne et al., 1995) and the relationship between disc displacement and TMJ stress distribution (Tanaka et al., 2000; Buranastidporn et al., 2004). However, the influences on TMJ stresses of asymmetric loading resulting from asymmetry of the mandible and their association with TMJ ID symptoms have not been investigated.

In finite element analysis, the precision of model construction verifies the predictability as well as the accuracy of the results. To determine the reliability of the model, previous studies compared their calculations with actual measurements made on a living human being. Calculated stresses at the articular disc of the model have been compared with measured synovial pressure in humans (Nagahara *et al.*, 1999). DeVocht *et al.* (2001) reported an experimental validation of the FEM by performing direct measurement of stresses in the upper compartment of the TMJ in fresh cadaver specimens.

The purpose of this study was to elucidate the relationship between biomechanical changes in the TMJ and TMJ ID symptoms in patients with vertical mandibular asymmetry.

Subjects and methods

This study was a retrospective analysis of existing data, and was performed in accordance with the guidelines of the Helsinki Declaration (1996).

Epidemiological study

Subjects. Consecutive adult patients with mandibular asymmetry associated with TMJ ID, routinely referred to the Orthodontic Clinic of the Tokyo Medical and Dental Hospital for treatment during 1999–2002 were included in this study. The subjects comprised 70 female and 70 male patients with a mean age of 24 years (range 18.0–45.3 years).

Inclusion criteria were: presence of TMJ ID, mandibular asymmetry in the vertical dimension, and over 18 years of age. Exclusion criteria were: a history of infection, tumours, rheumatoid disease, or injuries to the TMJ, other clinically significant pathology affecting the craniofacial region, and any congenital syndrome.

Symptomatic side of TMJ ID. Criteria for including a patient with TMJ ID were reports of orofacial pain in the TMJ according to the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD; Dworkin and LeResche, 1992), joint sounds, and limitation of mouth opening, as defined by the Helkimo index (Helkimo, 1974). The appearance of at least one symptom was considered as indicative of TMJ ID. The side with symptoms was categorized into ipsilateral and contralateral sides relative to the mandibular shift for each joint.

Cephalometric radiography and analysis. Posterioranterior (PA) cephalograms obtained routinely prior to orthodontic treatment were traced. The landmarks were identified and used for quantifying the inclination of the FOP, which represented the asymmetry in the vertical dimension. The vertical reference plane (the facial midline) was constructed as a straight line passing through crista galli and anterior nasal spine, perpendicular to a straight line between the intersections of the innominate line of the greater wing of the sphenoid bone and the lateral orbital margins. The angle measured between the perpendicular line of the facial midline and a straight line passing through the tips of the buccal cusps of the bilateral lower first molars was defined as the inclination of the FOP; a positive value indicating this plane inclined superiorly toward the ipsilateral side (the side to which the mandible shifted) (Figure 1a).

For each patient the degree of the inclination of the FOP and the side affected by TMJ ID symptoms were evaluated. To identify statistically significant relationships between the inclination of the FOP and the prevalence of the side with symptoms (ipsi- or contralateral), the differences in the mean values of the inclination of the FOP on each side were tested by analysis of variance (ANOVA). A probability value of less than 0.05 was considered to indicate statistical significance.

Error of the method. Lateral cephalograms and panoramic radiographs were used with PA cephalograms to identify the valid landmarks in the following way. The error of the method was determined by retracing each cephalogram on separate occasions, two weeks after the first tracing. The following formula was used for measurement error (Err) calculation:

$$\operatorname{Err} = \sqrt{\frac{\sum d^2}{2n}}$$

where *d* is the difference between the two measurements of a pair and *n* is the number of subjects. The mean double-determination errors in linear and angular measurement (Baumrind and Frantz, 1971; Ahlqvist *et al.*, 1986; 1988) were 0.5 mm and 0.5 degrees, respectively.

Mathematical study

Finite element model. Standard model: A virtual 3D computer model of the entire mandible, including the TMJ, was developed for the finite element analysis (Figure 1b), with a specially written program using an ASCII editable file. By modifying standard geometrical data of anatomical morphology (Ishida *et al.*, 1991), a model of the mandible, including the dental roots which were uniformly surrounded with a 0.2 mm-thick periodontal ligament (PDL) but without crowns, was first created. The normal occlusion of a subject was modelled using a non-contact-type surface morphology measurement system (XA-100S; Ono Sokki, Japan; Hisano and Soma, 1999). The model of the subject's occlusion was then connected to the roots of the lower dentition, adjusting the model of the mandible to the model of the occlusion so that it represented the average Japanese occlusion.

The TMJ was modelled as a two-layered 'cap' (Korioth *et al.*, 1992). The first layer of the cap consisted of the combined thickness of the condylar, articular, and temporal fibro-cartilage, based on their anatomical morphology and assuming a representative disc had a thickness of 2.3 mm at the anterior band, 0.9 mm at the intermediate zone, 2.7 mm at the centre, and 1.7 mm at the posterior band. The thickness of the disc at the medial and lateral poles was taken as 1.5 and 0.8 mm, respectively (McDevitt, 1989). The second layer of the cap was a part of the temporal cortical bone.

The components were integrated into the model and the material behaviours were assumed as linearly elastic. The



Figure 1 (a) The cephalometric landmarks, reference planes, and measurements of the frontal occlusal plane (FOP) used in the epidemiological study. (b) One of the asymmetric models with 6 degrees of frontal occlusal and mandibular plane inclination toward the left side used in the mathematical study. (c) The left temporomandibular joint (TMJ), showing the geometric relationship between the condyle, articular disc, and part of the temporal bone. (d) Top and lateral views of left articular-disc geometry. ROT, rotation angle.

material properties of each component were based on previous studies (Chen and Xu, 1994; Tanaka *et al.*, 1994). This model we described as the standard model, and comprised 55 981 nodes and 47 643 solid elements.

Asymmetrical-mandibular model: The FOP and FMP, which run bilaterally through the antegonial notches, as observed clinically, were significantly closely related (r = 0.91, P < 0.01) and could be considered as a single structure that moves in the same direction by the same amount. The asymmetry of the model was established by rotating the FOP and FMP. The centre of rotation was located at the midpoint of the occlusal plane. The right and left ramus heights were altered to maintain the vertical height of the mandible. Both TMJs were fixed at the same position and remained symmetrical in shape. The asymmetry resulted in changes in the direction of the bite force and of the muscle forces acting on the TMJ. From these relationships, 10 asymmetric models were created with FOP and FMP inclined by 1–10 degrees in 1 degree increments ascending to the left side.

Loading and constraint conditions. For the loading conditions, the forces and lines of action of the masticatory muscles were determined. The models were then loaded with multiple force vectors to simulate the absolute moment of muscle forces during clenching over wide areas of attachment. The force magnitude was determined to exert a resultant force under the assumption that the force is proportional to the area of the cross-section (Korioth and Hannam, 1990). The resultant force of 500 N (Tanaka *et al.*,

1994) was exerted by the lateral pterygoid, medial pterygoid, masseter, and temporal muscles at a ratio of 1:2:2:4, respectively (Ishida *et al.*, 1991).

During loading, the upper surfaces of the glenoid fossa of the temporal bone and the base of the upper dentition were completely fixed to prevent a sliding movement of the entire model.

Model and data analysis. Simulations of the FEMs were performed using commercially available finite element software (NISA II; Engineering Mechanics Research Corp., Troy, Missouri, USA). All models were calculated using linear static analysis. For stress analyses, von Mises stress (defined as a mathematical combination of all components of both axial and shear stresses) was used to represent the total stress in a given region of the model.

Disturbances affecting only the articular disc were considered in this study. The stress distributions of the articular disc from each model were compared between the right and left sides of the asymmetric model and with those of the standard model. Furthermore, stress loading in the asymmetric model was compared with the prevalence of TMJ ID in the patients.

Results

Epidemiological study

Prevalence of symptomatic side. TMJ ID symptoms were reported in 187 of the 280 joints. Fifty-five were ipsilateral, 40 contralateral, and the remainder bilateral. The symptoms of each joint are shown in Figure 2. Joint sounds were reported by all patients. One hundred and five patients had only joint sounds, 51 joint sounds with orofacial pain, eight joint sounds with limitation of opening and 23 had all symptoms.

The prevalence of the symptomatic side according to the degree of inclination of the FOP is illustrated in Figure 3. The symptoms were found primarily on the ipsilateral side in the patients with mild degrees of inclination. Increasing the degree of inclination reduced the percentage of symptoms on the ipsilateral side but increased the symptoms on the contralateral side. Significant differences in the mean values of the inclination of the FOP for each symptomatic side were found (P < 0.01).

Mathematical study

Finite element analysis. Changes of TMJ stresses according to the degree of inclination of the FOP are illustrated in Figures 4 and 5. Figure 4 shows the changes in the pattern of stress distribution and Figure 5 the amount of stress.

Standard model: The mean value of von Mises stress was 0.1 MPa, and the maximum value was 1.33 MPa; right and left discs appeared to be loaded symmetrically in both amount and pattern.



Figure 2 Epidemiology of internal derangement symptoms on the ipsilateral and contralateral side of the temporomandibular joint (TMJ).



Means for groups in homogeneous subsets are displayed

Uses Harmonic Mean Sample Size = 46.808.

The group sizes are unequal. The harmoic mean of the group sizes is used.

* The mean difference is significant at P < 0.01

Figure 3 An increase in the degree of the inclination of the frontal occlusal plane (FOP) resulted in a decrease in the percentage of symptoms on the ipsilateral side and a corresponding increase in the symptoms on the contralateral side.

Asymmetrical-mandibular model: The patterns of stress distribution on the side to which the disc was displaced differed from the standard model as the amount of asymmetry increased. On the ipsilateral side, the distribution showed a marked shift in direction, and the medial portions were loaded least, with the stress to the lateral part gradually increasing. For the contralateral disc, the medial borders were additionally loaded; however, a pattern of stress distribution that gradually increased from the centre to the border remained (Figure 4b).



Figure 4 The (a) articular disc of the standard model and (b) the disc from the joint which had suffered displacement. There was a clear change in the stress distribution from the standard model. ROT, rotation angle.

The mean stress values on the ipsilateral disc were smaller than those in the standard model and those on the contralateral side. Increases in the amount of asymmetry slightly decreased the stress on the side to which the disc had been shifted. There was no direct relationship between the symptoms and the reduction in stress in the disc on the ipsilateral side, the side which had suffered disc displacement. An increase in symptoms was associated with the increasing stress load on the contralateral side (Figure 5).

Discussion

Several studies have been conducted to investigate associations between mandibular asymmetry and TMJ ID but there has been no report of a clear relationship. In the present study the amount of vertical asymmetry in the FOP was associated with the prevalence of the symptoms of TMJ ID in the joint which was displaced. To explain this phenomenon, the finite element analytical method was used to evaluate the biomechanical changes in the TMJ. Using the FEM, confounding factors were excluded and the influences of the frontal occlusal cant to the load on the TMJ were determined.

Since analytical results of the finite element method are highly dependent on the models developed, in the present study the results of calculations were compared with those of actual measurements of a living human (Nitzan, 1994) to determine the accuracy of the models. Normal stress at the centre of the upper surface of the articular disc in the standard model was assumed to represent the stress in the articular cavity of the TMJ. The normal stress in the standard model under restraint conditions was a compression stress of 8.64 MPa (64.81 mmHg). This value is similar to the synovial pressure in humans at the intercuspal position, 8.51 MPa (63.9 mmHg), reported by Nitzan (1994). The results of this comparison indicated that the model possessed sufficient physical and biomechanical realism to investigate stresses within the human TMJ.



Figure 5 The relationship between maximum stress loading on the articular disc in model simulations and prevalence of temporomandibular joint internal derangement (TMJ ID) in the contralateral joint (a) and the ipsilateral joint which had suffered internal derangement (b), both compared with the inclination of the frontal occlusal plane. An increase in symptoms is associated with increasing stress load on the contralateral side.

Mechanical disturbances in the articular disc in mandibular asymmetry

Vertical asymmetry influenced the differential pattern of mechanical loads of the articular disc both in direction and magnitude. Such disturbances of stresses have been considered a mechanism underlying joint impairment (Stegenga, 2001).

Effect of disturbances in the amount of stress. The increasing prevalence of symptoms in the contralateral TMJ with the amount of asymmetry is in agreement with the observation in the present study that the stress on the contralateral disc increases in proportion to the degree of vertical asymmetry. The maximum stress in the models was found to be more than 1.5 MPa, which exceeds the elastic limit of the articular disc (Tanne *et al.*, 1991) when it was inclined more than 3 degrees. This suggests that increases in the magnitude of stress are directly related to TMJ ID. However, the articular disc is able to dissipate load (Osborn, 1985; Beek *et al.*, 2001), which allows the TMJ to resist and adapt to increasing stresses up to its viscoelastic limit (Chin *et al.*, 1996; Tanaka *et al.*, 2000).

Concerning the decrease in stress on the ipsilateral side, it has previously been accepted that inadequate loading causes a decrease in anabolic activity (i.e. insufficient proteoglycan synthesis) which diminishes bone formation (Sasaguri *et al.*, 1998; Kiliaridis *et al.*, 1999) and is associated with a weak joint structure (Luder, 1993; Stengenga, 2001). However, no direct relationship between the symptoms and the decrease in stress in the disc on the ipsilateral side was found in the present study.

Effect of disturbances in the pattern of stress distribution. The symptoms on the ipsilateral side were derived from a different mechanism, the disturbance in the direction of load, which also contributes to TMJ ID. The altered pattern of stress distribution, a consequence of the disturbance in the direction of TMJ load, may influence articular disc displacement particularly medially and laterally. Repetitive loading with unbalanced and inappropriate directions of stress may cause a reaction in the lateral pterygoid muscle (Stegenga et al., 1989) and the accessory ligament around the TMJ (Osborn, 1995), which may decrease the stability of the joint. These mechanical strains may cause fatigue and spasm of the muscles and ligaments which finally allow disc displacement. However, in contrast to the mechanism of overload, simple disc displacement due to inappropriate directional loading may in some cases adapt and resolve spontaneously (Lundh et al., 1992).

Conclusions

The findings of this research show that vertical asymmetry affects TMJ ID. However, TMJ ID itself may be a cause of growth disturbances which result in mandibular asymmetry. It is also important to note that other occlusal or skeletal characteristics, including mandibular asymmetry, selfadaptation, dentoalveolar compensation and remodelling in the bone and joint, can have a positive or negative influence on TMJ ID, and studies are required to achieve a better understanding of these factors.

This work has clinical implications: whereas the causes of TMJ ID are multifactorial, it is suggested that disturbances in stress distribution due to vertical asymmetry of the mandible, both in amount and direction, contribute to TMJ ID and these should be considered when formulating orthodontic and/or orthognathic treatment plans in an attempt to establish a flat occlusal plane.

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