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Temporomandibular joint adaptations following two-phase therapy: an MRI study

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Structured Abstract
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Aim – To document the alterations within the condyle-glenoid fossa (C-GF) complex and the positional changes of the glenoid fossa in the cranium after removable functional appliance therapy and after the completion of fixed appliance therapy.
Setting and Sample – The Department of Orthodontics, Centre for Dental Education and Research, All India Institute of Medical Sciences, New Delhi, India. The study sample consisted of 12 growing children (eight girls and four boys) between 10 and 14 years of age with skeletal Class II division 1 malocclusion selected on well defined criteria.
Materials and Methods – All patients were treated with either the Twin Block or the Bionator appliance followed by fixed appliances. Mean total treatment duration was 28 months. The changes in and around the C-GF complex were evaluated using MRI at pre-treatment stage, after functional appliance therapy and at the completion of fixed mechanotherapy.
Results – Forward condylar position within the glenoid fossa and articular disc retrusion with respect to the condylar head were statistically significant after functional appliance therapy. However, the condyles had a relatively concentric position within the glenoid fossa, while the articular disc resumed its pre-treatment position at the end of the treatment. Linear measurements from the centre of the external auditory meatus to the post-glenoid spine revealed a 1.3-mm forward relocation of the post-glenoid spine along the Frankfurt Horizontal plane.
Conclusions – Forward relocation of the C-GF complex seems to be one of the mechanisms of action of functional appliances, while the internal anatomic arrangement within the temporomandibular joint (TMJ) complex normalizes to its pre-treatment position.

Key words: articular disc; functional appliance; glenoid fossa; mandibular condyle; MRI; orthodontics

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Introduction

Functional appliances have been used for more than 100 years in the field of orthodontics and dentofacial orthopedics for the correction of mandibular retrognathia preferably during active skeletal growth (1). There are a variety of mechanisms by which functional appliances are known to act (2), such as dentoalveolar changes, restriction of maxillary growth, altered expression of mandibular growth, redirection of condylar growth, changes in neuromuscular anatomy and function that would induce bone remodeling, and adaptive changes in glenoid fossa location. Currently there seems to be a little consensus among researchers about the mode of action of these appliances (3, 4).

Woodside (2) stated that the missing link in all studies appears to be the lack of consideration for glenoid fossa relocation. It is believed that growth modulation of the condylar cartilage and adaptive changes in the glenoid fossa may be important mechanisms for the action of mandibular advancement functional appliances.

Various animal studies have documented temporal bone and condylar adaptation to protrusive mandibular function. It has been proposed that the condylar cartilage, in contrast to epiphyseal plates of long bones, reacts positively to mechanical stimulation (5, 6). Adaptation of the condylar cartilage to mandibular forward positioning constitutes the fundamental rationale for orthodontic functional therapy. Shen and Darendeliler (7) documented that the adaptive remodeling of the condylar cartilage proceeds with the biomolecular pathway initiating from chondrogenesis and finishing with osteogenesis. Liu et al (8) documented that mandibular lateral shift in rats caused asymmetry in the position and size of the glenoid fossa and that this phenomenon was related to different bilateral directional new bone formation in the posterior region of the glenoid fossa. Proff et al (9) showed that the zonal structure of the condylar cartilage in pigs, may be modified by an altered spatial relationship between the mandibular condyle and the glenoid fossa. Xiong et al (10) showed that mechanical strain produced by mandibular advancement induces neovascularization and osteogenesis leading to adaptive growth of condyle in rats. Rabie et al (11) found that mandibular protrusion in rats resulted in the osteoprogenitor cells being oriented in the direction of the pull of the posterior fibers of the disc and also resulted in a considerable increase in bone formation in the glenoid fossa. They also showed (12) that forward mandibular positioning causes changes in the biophysical environment of the TMJ of adult rats that leads to condylar adaptation and formation of new cartilage in the posterior part of the condyle. Similar findings have been reported in other studies on rats (13–15), sheep (16), rabbits (17) and monkeys (5, 18, 19). Voudouris and Kuftinec (20) proposed that mandibular advancement appliances stretch the fibrocartilagenous lining of the glenoid fossa resulting in increased appositional bone formation, while the transduction of forces causes increased appositional bone formation in the glenoid fossa away from the site of retrodiscal tissue attachment. Voudouris et al. (21) demonstrated that Herbst therapy in monkeys caused an altered vector of growth of the glenoid fossa to meet active condylar shape modification which caused its inferior and anterior relocation.

Before the advent of MRI, various techniques have been used to image the TMJ which include cephalograms (22–24), orthopantomograms (25, 26) and tomograms (27–30), bone scintigraphy (31) with radiologic markers like ^{99m}Tc-MDP, arthroscopy and arthrography (32–37), and CT scanning (27, 29). MRI, a multiplanar imaging technique, has the advantage of giving an accurate assessment of both the bony and the soft tissues (38, 39). This technique is believed to be non-invasive, radiation free and gives more superior contrast resolution than any other imaging modality (38, 39). MRI is considered the imaging modality of choice for assessment of internal derangements of the temoporomandibular joint (40).

MRI studies on fixed functional appliances (FFA) (41–45) document that the condyle and the articular disc, which are significantly displaced from their positions during FA therapy, return to their pre-treatment positions at the end of treatment. However, the results documented with FFA may or may not hold true for removable functional appliances (21). Effects of removable functional appliances on the condyle-glenoid fossa (C-GF) complex have been studied with respect to the Fränkel, Activator, Twin block and Bionator appliances. While Franco et al (46) found that Fränkel therapy resulted in a 'more normal' articular disc morphology, Ruf et al. (47) found that a pre-treatment physiological disc-condyle relationship was unaffected by Activator therapy. Arat et al. (48) also found that changes in the disc position were insignificant after 6 months of activator therapy. Watted et al. (49) concluded that Bionator therapy resulted in normal position of the mandibular fossa, the condyle and the disc-condyle relationship. Chintakanon et al.

(50) concluded that Twin Block therapy had neither positive nor negative effects on disc position, and there was little evidence that the disc was recaptured. They also noted anterior positioning of the condylar head (CH) in the glenoid fossa after 6 months of Twin Block therapy.

It should be noted that all of above studies are limited to the phase of removable functional appliance therapy only, and changes in the C-GF complex at the completion of a second phase of occlusal settlement with fixed appliance are not reported in literature. Moreover, no MRI study has attempted to evaluate the changes in the position of the C-GF complex following removable functional appliance therapy. Therefore, the aim of the present MRI study was to document the changes brought about in the internal anatomical relationships of the TMJ complex and, the positional changes of the glenoid fossa with respect to adjacent structures of the cranium brought about by treatment with: 1) removable functional appliances and 2) after completion of occlusion settlement with fixed appliances.

Subjects and methods

Subjects

The study was initiated on a selected sample of 14 growing patients (four boys and ten girls) in the age range of 10–14 years with Class II division 1 malocclusion, increased overjet and deep bite, retrognathic mandible, low anterior facial height and an average growth pattern confirmed cephalometrically. Subjects with a history or symptoms of temporomandibular joint disease, history of previous orthodontic interventions or systemic diseases affecting bone metabolism were excluded. Informed consent from the parents and patients was obtained prior to the start of the study. Following detailed clinical and cephalometric analysis, and treatment planning, seven patients began treatment with a standard design Twin Block appliance (three boys and four girls) and another seven with the conventional Bionator appliance (one boy and six girls).

All the patients underwent functional appliance therapy to achieve Class I occlusion for an average of 10 months, followed by a second phase of treatment with a pre-adjusted edgewise appliance in Roth's prescription for settling of the occlusion. The mean duration of fixed appliance therapy was 18.5 months. The mean total duration of active treatment including both functional and fixed phase was 28.5 months.

One patient from each group (both girls) did not follow the treatment as prescribed and were excluded from further study. Thus, the final sample size for the study was reduced to 12 patients (eight girls and four boys).

All records, including MRI scans, were collected at three stages: 1) Stage I (pre-treatment), 2) Stage II (minimum of 6 months of functional appliance therapy or after correction to Class I molar relation) and 3) Stage III (after completion of fixed mechanotherapy).

Recording of the MRI

MRI scans of the TMJ were obtained with a Magnetom 1.5 Tesla Sonata (Siemens, Erlangen, Germany) scanner equipped with dedicated TMJ surface coils for simultaneous imaging of left and right joints. The sagittal images were taken perpendicular to the long axis of the CH and the coronal images were taken parallel to the long axis of the CH. The images were recorded in maximum intercuspation before treatment and after completion of the second phase of therapy, and in the most retruded position after sagittal correction or after 6 months whichever was earlier.

The MRI protocol included T1 weighted (T1W) spin echo sequences (TR 400/TE 15/FoV 160 × 160 mm) and T2 weighted (T2W) spin echo sequence (TR 2500/TE 66/FoV 160 × 160 mm), in coronal and sagittal planes of 3 mm slice thickness with no interslice gap.

Evaluation of MRI

Each MRI scan was carefully evaluated visually. Both the T1 and T2 weighted sequences in the coronal and sagittal planes were evaluated for documenting the changes in the morphology of the CH, articular disc and glenoid fossa. Parameters evaluated included any visible changes in shape, morphology and position of the anatomic structures mentioned above. Any pathological findings, such as spur/osteophyte formation or abnormal resorption areas on the CH and perforation or loss of contour of the articular disc, were carefully looked for and recorded.

The MRI scans were further evaluated for sagittal concentricity, eminence angle, sagittal disc position, glenoid fossa angle and linear metric measurements, which were measured on the sagittal section passing through the central part of the condyle, and for the coronal disc position in the coronal section. The sagittal section so chosen displayed the maximum length of the posterior border of the condyle and ramus while coronal disc position was measured from the coronal image exhibiting the widest part of the condyle.

The eminence angle and the sagittal disc position were measured in relation to two reference lines: the posterior condylar line (PC line) and the Frankfurt Horizontal plane (FH Plane). The PC line was drawn directly on the MRI scan, while the FH plane was transferred from the lateral cephalogram to the MRI scan (Fig. 1a–c), according to the method given by Nebbe et al. (51).

Sagittal condylar concentricity was evaluated using the method described by Pullinger et al. (52) (Fig. 2). A positive value indicated an anterior position of the condyle, while a negative value indicated a posterior position of condyle and zero value was referred to as concentric.

The eminence angle, the sagittal disc position and the coronal disc position were evaluated by the method described by Chintakanon et al. (50). The eminence angle was measured as the angle formed by a line tangential to the posterior slope of the articular eminence relative to PC line and FH plane (Fig. 3). The sagittal disc position was evaluated using PC line (Fig. 4a) and FH plane (Fig. 4b). The intersecting point between a line parallel to the PC line passing through the condylar centre and the roof of the fossa was constructed and was referred to as the 12 O' clock position in the glenoid fossa. The line perpendicular to the FH plane through the condylar centre and the roof of the articular fossa was constructed and referred to as the 12 O' clock position. The position of the anterior and posterior band of the disc was measured as angles relative to the 12 O' clock position (Fig. 4a,b). The position of the posterior band of the disc was used to classify the disc position as anterior displacement,

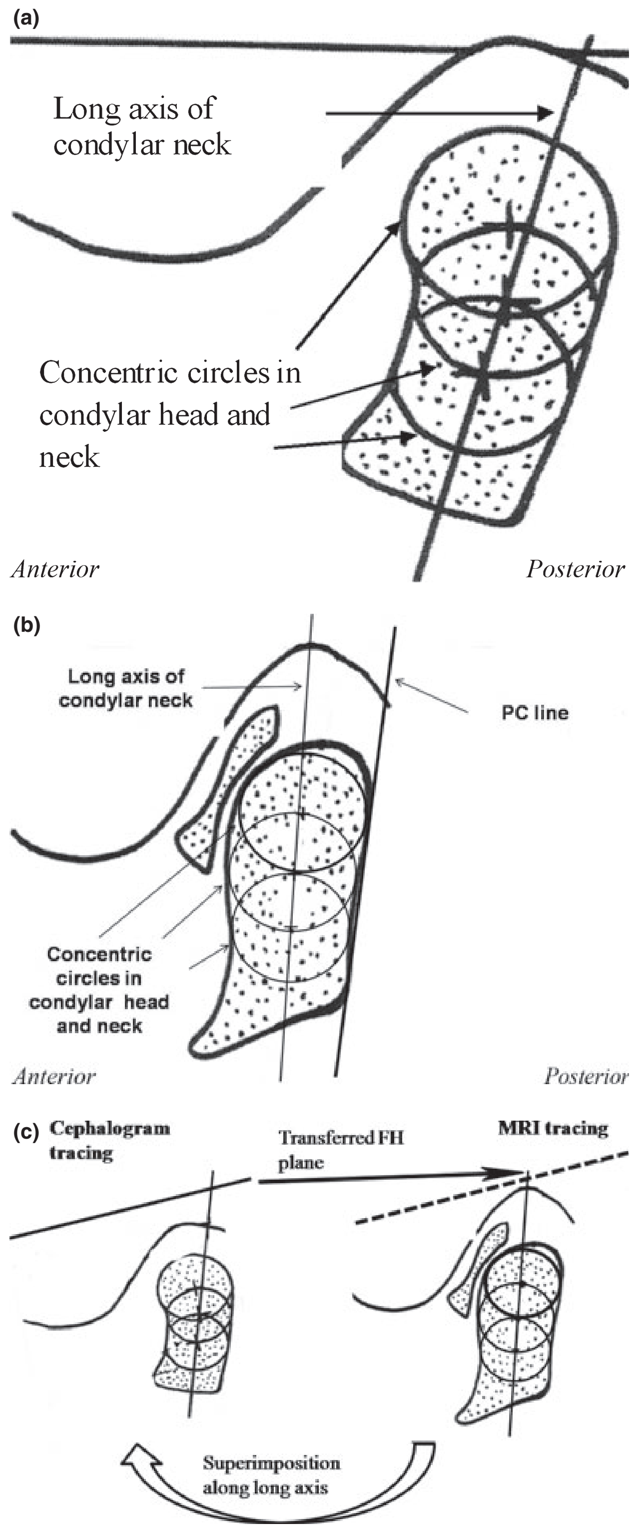

Fig. 1. Sagittal view of the condylar neck and head showing transfer of the FH plane from lateral cephalogram to MRI scan. (a) Determination of the long axis of the condylar neck on cephalogram. Three concentric circles drawn in the condylar head and neck region confined within the outer cortical margins. The first circle is drawn in the condylar head. Two more successive circles are drawn in the neck region such that the circumference of each of them passes through the centre of the previously drawn circle. A line joining the circle centers in the condylar neck region is considered as the long axis of the condylar neck. (b) Determination of the long axis of the condylar neck on MRI. The same method as in (a) was applied to identify the condylar neck long axis on MRI tracings. (c) Transfer of FH Plane from cephalogram to the MRI scan. Superimposition of the tracings along the long axes of the condylar neck allowed transfer of the FH plane from cephalogram to MRI.

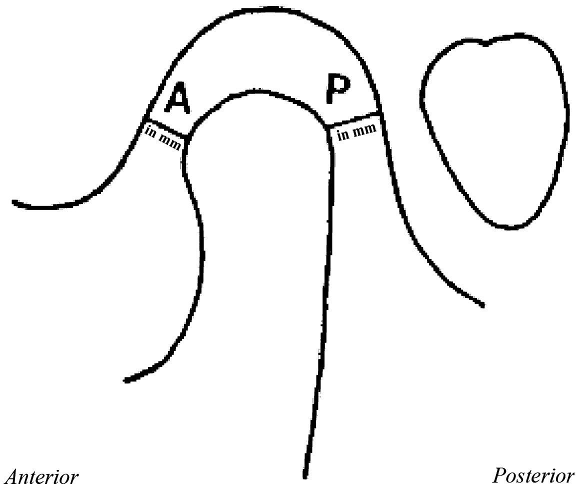

Fig. 2. Sagittal section of MRI demonstrating evaluation of sagittal concentricity. Formula: $(P - A/P + A) \times 100 = \%$ of displacement, where A represents narrowest anterior interarticular joint space and P represents narrowest posterior interarticular joint space.

normal or posterior displacement. The coronal disc position was evaluated by constructing a long axis along the CH and neck (Fig. 5). The line across the maximum width was then divided into tenths. The position of the disc was recorded in relation to the 1/10 divisions of the condylar width. Negative value represented the lateral side, while positive value represented the medial side. This method was preferred, rather than using absolute values, to overcome the differences in size of individual condyles (50).

The glenoid fossa angle was measured on the sagittal films as the angle between the tangents to the anterior and posterior slopes of the glenoid fossa (Fig. 6). The position of the glenoid fossa, and that of the condyle (Fig. 7), was evaluated with respect to the centre of the external auditory meatus (c-EAM). The c-EAM was

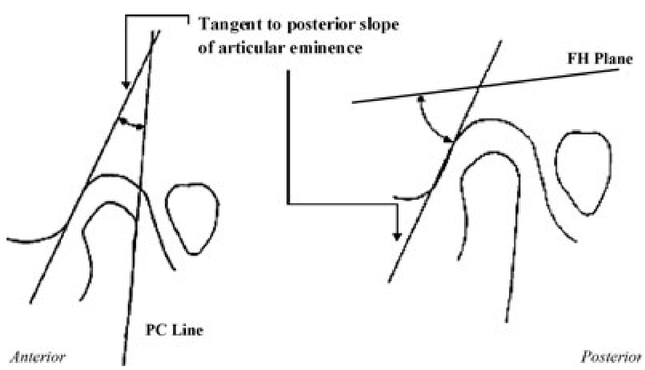

Fig. 3. Sagittal section of MRI showing determination of eminence angle. A = Angle between the line tangent to posterior slope of articular eminence and posterior condylar (PC) line; B = Angle between the line tangent to posterior slope of articular eminence and Frankfurt horizontal (FH) line.

defined by the intersection of two lines, one along the maximum length, and the other along the maximum width of the EAM (Fig. 7). A perpendicular was dropped from the transferred FH plane such that it passed through the constructed c-EAM. Two points were then marked, one at the crest of the post-glenoid spine (c-PGS) and the other at the centre of CH (c-CH). The linear distances of the c-CH and the c-PGS, from the c-EAM, were evaluated as the shortest distance from the constructed FH perpendicular. The linear

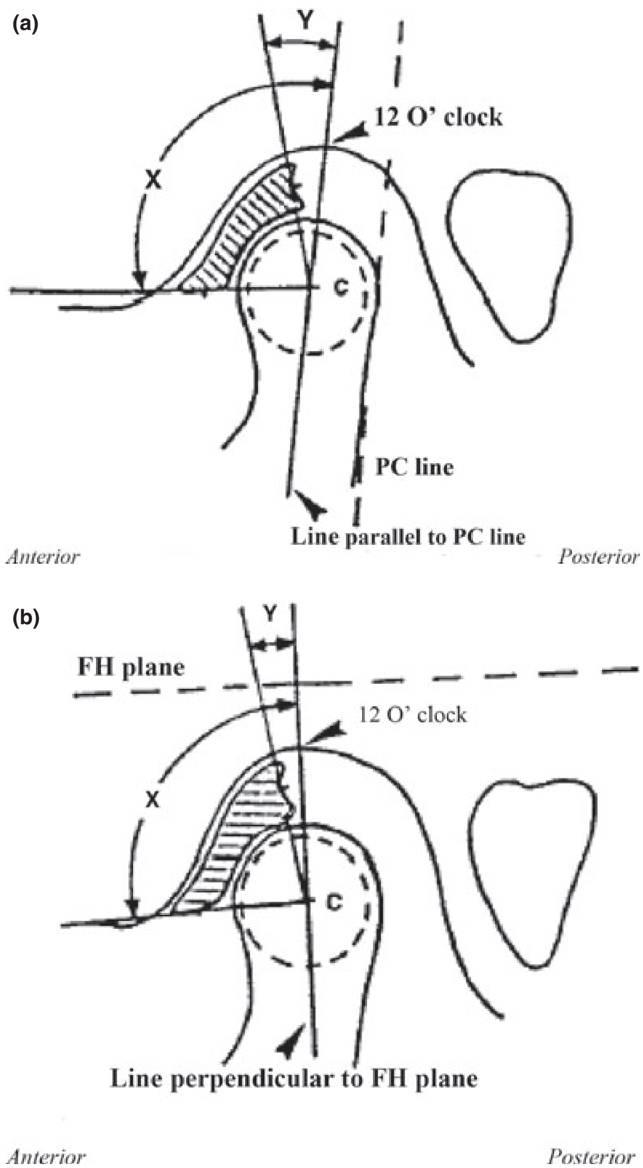

Fig. 4. Sagittal section of MRI showing determination of sagittal disc position. (a) Determination of disc position relative to the 12 O'clock position using the PC line. Angle of anterior band of disc to PC line (X). Angle of posterior band of disc to PC line (Y). (b) Determination of disc position relative to the 12 O'clock position using the FH plane. Angle of anterior band of disc to FH plane (X). Angle of posterior band of disc to FH plane (Y).

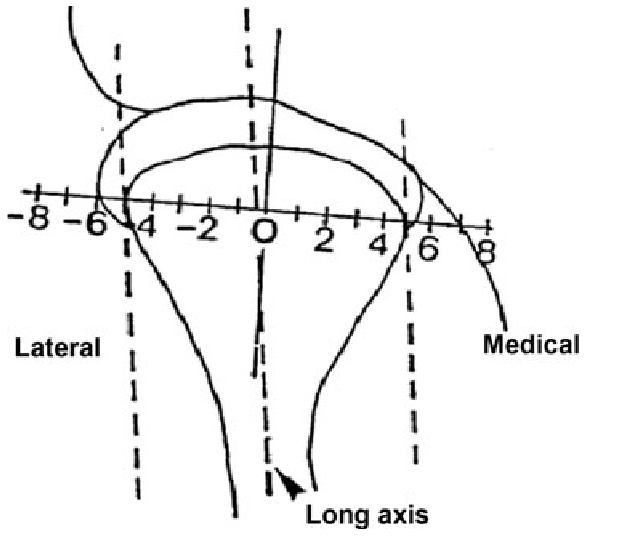

Fig. 5. Coronal section of MRI showing determination of coronal disc position. Negative value represents the lateral side; Positive value represents the medial side.

measurements were adjusted by dividing the recorded value by the magnification factor of the individual MRI films, which varied from 1.3 to 2.1, to obtain the true linear separation between the points.

Statistical analysis and measurement of error

All the MRI scans were traced and analysed by a single investigator. On an average, 6–7 MRI scans were analysed in a day to reduce error due to investigator fatigue. 'SPSS 12' software program was used for statistical analysis. To determine the intra-investigator error, 10 randomly selected MRI scans were analysed at two separate occasions and the error was calculated. Altman's analysis (53) was applied to check for agreement between calculated values. The errors evaluated were within acceptable limits (Table 1).

Friedman test was applied to test the statistical significance of the results, when stages I, II and III were compared. Where the Friedman test indicated a significant result, Neuman Kuel range test was applied to test the statistical significance individually between the three stages of treatment. Probability value (*p*-value) less than 0.05 was considered statistically significant.

Results

Visual evaluation

On pre-treatment sagittal films, the condyles presented a slightly flat contour on the postero-superior surface, and a slight notch like projection (Fig. 8a) on the anterior surface which is the site of insertion of lateral pterygoid muscle. The glenoid fossa was bell-shaped with asymmetric slopes. These MRI findings are consistent with the normal anatomy of these structures.

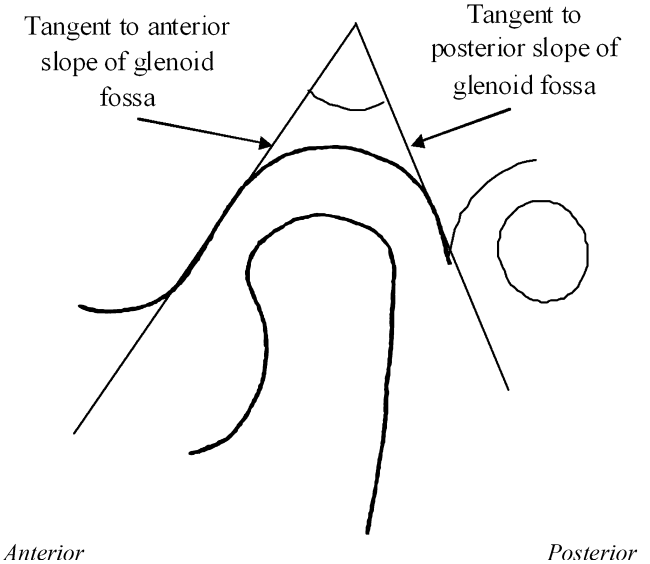

Fig. 6. Sagittal section of MRI showing determination of glenoid fossa angle. The angle is formed between the anterior and posterior slopes of glenoid fossa.

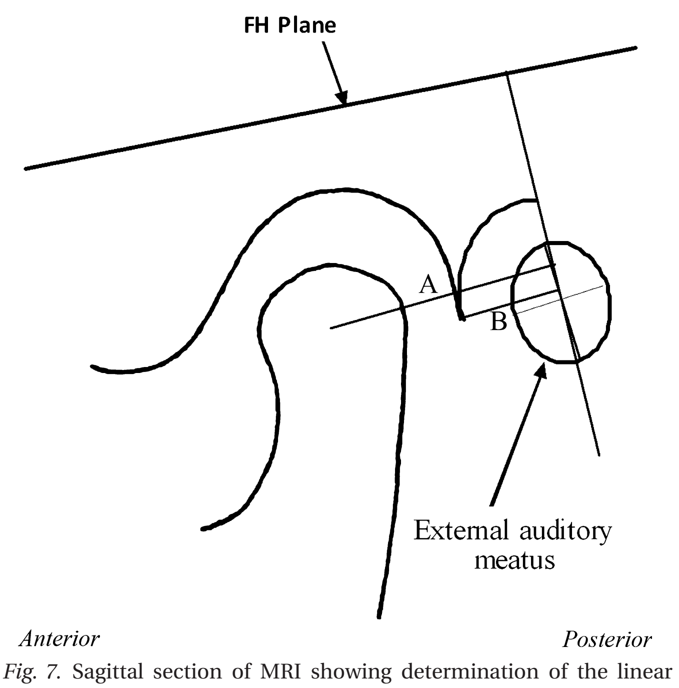

Fig. 7. Sagittal section of MRI showing determination of the linear distance. (A) Linear distance between FH perpendicular to the centre of external auditory meatus and centre of mandibular condyle. (B) Linear distance between FH perpendicular to the centre of external auditary meatus and the tip of the post-glenoid spine.

Table 1. **Measurement errors for the variables used in the study**

			Altman's criteria					95% confidence interval of the difference	
S. no.	Variable	SE	r	r′	β	ICC	d	Lower	Upper
1	Sagittal concentricity (%)	0.225	0.997	0.09	0.998	0.998	0.45	−0.375	0.157
2	Eminence angle in respect to PC line (°)	0.315	0.98	0.009	0.988	0.997	0.009	−0.729	0.911
3	Eminence angle in respect to FH plane (°)	0.124	0.99	0.098	0.997	0.98	−0.09	−1.015	0.833
4	Anterior band of disc (PC) (°)	0.084	0.987	−0.16	0.999	0.977	−0.27	−1.014	0.469
5	Anterior band of disc (FH) (°)	0.511	0.994	0.013	0.981	0.999	0.001	−0.901	0.901
6	Posterior band of disc (PC) (°)	0.119	0.977	−0.3	0.986	0.991	0.13	−0.364	0.637
7	Posterior band of disc (FH) (°)	0.368	0.995	−0.266	0.994	0.96	0.09	−0.793	0.611
8	Linear glenoid fossa (LGF) displacement (c-CH) (mm)	0.415	0.927	−0.5	0.977	0.97	0.001	−0.275	0.275
9	LGF displacement (PGS) (mm)	0.333	0.981	0.01	0.968	0.988	0.04	−0.141	0.232
10	Glenoid fossa angle (°)	0.405	0.986	0.08	0.98	0.990	0.45	−0.684	1.593

None of the joints revealed any evidence of osseous anomalies or pathological findings related to the shape or integrity of the articular disc/retrodiscal tissues.

At stage II, eight of the 12 cases showed visually detectable changes on the MRI scans. Appearance of convexity on the postero-superior surface of the CH, and reduction in the prominence of the notch on the anterior surface were the prominent findings (Fig. 8b). At stage III, a tendency for the pre-treatment features to reappear was observed (Fig. 8c). There was re-appear-

Fig. 8. Sequential sagittal oblique views of the TMJ (right side) of case SB showing MRI changes in the condylar head morphology at the three stages of treatment. (a) Pre-treatment anatomy of the condyle and the TMJ complex. Arrows indicate i) the prominent notch on the anterior surface, and ii) the flat contour on the postero-superior surface of the condylar head. (b) Changes in condylar head morphology and the TMJ after functional appliance therapy (6 months). Arrows indicate i) increase in the superior joint space and ii) loss of the anterior notch, and the flat contour on the posterosuperior surface of the condylar head. (c) Changes in the condylar head morphology and the TMJ after fixed appliance therapy (28 months). Arrows indicate reappearance of the pre-treatment contours on the condylar head. Reduction of the superior joint space is also evident.

ance of the flat contour on the postero-superior surface, and the notching on the anterior surface, of the CH in these eight cases. The features resembled those seen at the pre-treatment stage, but were more appreciable and better defined.

Comparison of stage I and stage III MRI scans revealed only minor changes in the anatomy of C-GF complex. No pathological findings were detected with respect to the condyle, glenoid fossa and the articular disc in any of the cases. No changes in the MR signal intensity in the glenoid fossa or the CH could be detected in any of the cases and no double contours were observed.

Sagittal concentricity

At pre-treatment, nine of the 12 cases had anterior condylar position in the glenoid fossa, while three patients had a posterior condylar position (Table 2). At stage II, 10 of the 12 patients showed an anterior condylar position and two showed concentric condylar position. Overall, the condylar position had shifted anteriorly in the glenoid fossa and the anterior joint position became the most common joint position after 6 months of functional appliance therapy. The condyles, which were initially anteriorly positioned in the glenoid fossa, shifted more anteriorly while the posteriorly positioned condyles also came forward to assume either an anterior (one case) or a concentric position (two cases) in the glenoid fossa.

At stage III, the condyles showed a tendency to move posteriorly in the glenoid fossa, and the number of cases with anteriorly positioned condyles decreased from 10 at stage II to eight at stage III. Also the number of cases with posterior condylar positions increased from zero at stage II to three at stage III, while one case assumed a concentric condylar position. Out of those cases in which the condyles maintained their anterior condylar positions at stage III, the post-treatment values suggested that the condyles had shifted posteriorly when compared with their pre-treatment positions, and were thus closer to the absolute concentric condylar position in the glenoid fossa.

Table 2. **Distribution of the sagittal condylar position in total sample (n = 12)**

		Pre-treatment			
		Anterior	Concentric	Posterior	Total
After 6 months	Anterior	9	0	1	10
	Concentric	0	0	2	2
	Posterior	0	0	0	0
	Total	9	0	3	12
After fixed therapy	Anterior	8	0	0	8
	Concentric	0	0	1	1
	Posterior	1	0	2	3
	Total	9	0	3	12

Eminence angle

Changes in the eminence angle were inconsistent and overall, no statistically significant change in the eminence angle could be seen during the three stages of treatment (Table 3).

Sagittal disc position

Statistically significant changes in the mean position of both the anterior and the posterior bands of the articular disc were noted ($p < 0.05$) for the three stages of treatment, with respect to both the PC line and the FH plane (Table 3). Both the anterior and the posterior bands shifted posteriorly between stages I and II. The shift was statistically significant with respect to, both the reference lines for the anterior band, and with respect to the PC line for the posterior band ($p < 0.05$). However, between stage II and stage III, both the anterior and the posterior band demonstrated reversal of the previous trend and shifted anteriorly over the CH. The anterior shift was statistically significant for both the bands, with respect to both the reference lines ($p < 0.05$).

When stage I was compared with stage III, no statistically significant change in the position of either the anterior or the posterior band of the disc could be found (compared with their pre-treatment positions), with respect to either of the reference lines.

Coronal disc position

Nine of the 12 patients revealed an articular disc placed centrally over the CH in the coronal sections; two revealed a laterally displaced disc while one showed a medially displaced disc, in respect to the CH (Table 4). None of the patients, however, showed

Table 3. **Comparison of eminence angle and sagittal disc position in the complete sample (n = 12)**

Variables (in degree)	Pre-treatment†	Post-functional†	After 2nd phase therapy†	*p* value	Significance
Relative to PC line					
Eminence angle	23.8 ± 11.0	25.5 ± 7.7	25.2 ± 9.6	0.667	NS
Anterior band of disc	117.2 ± 13.6	104.7 ± 11.1	114.3 ± 9.8	0.001	*
Posterior band of disc	13.3 ± 11.7	8.1 ± 10.0	13.2 ± 11.3	0.002	*
Relative to FH line					
Eminence angle	43.1 ± 11.9	41.8 ± 8.7	41.0 ± 7.5	0.938	NS
Anterior band of disc	96.3 ± 10.8	85.5 ± 7.8	92.3 ± 7.3	0.001	*
Posterior band of disc	–10.2 ± 10.0	–13.2 ± 7.3	–8.8 ± 7.7	0.040	*

NS, not significant; *$p < 0.05$.
†Values in Mean ± SD

any signs or symptoms of temporomandibular joint dysfunction. During the course of treatment, the status of the disc did not change relative to the CH and there was no MRI evidence of alteration of the coronal disc position, or of disc recapture, after 28 months of two-phase treatment with functional and fixed appliances. Additionally, none of the patients developed any clinical signs or symptoms of temporomandibular joint dysfunction during the course of treatment.

Glenoid fossa angle

No statistically significant changes were found in the glenoid fossa angle among the stages I, II and III of treatment (Table 5).

Table 4. **Distribution of coronal disc position in the complete sample (n = 12)**

		Pre-treatment			
		Lateral	Center	Medial	Total
Post-functional (6 months)	Lateral	2	0	0	2
	Center	0	9	0	9
	Medial	0	0	1	1
	Total	2	9	1	12
Post-fixed therapy	Lateral	2	0	0	2
	Center	0	9	0	9
	Medial	0	0	1	1
	Total	2	9	1	12

Sagittal position of the condyle and the PGS

The overall comparison among the three stages of treatment revealed a statistically significant change in the position of the c-CH ($p < 0.05$) (Table 6). The linear measurement from c-EAM to c-CH revealed a forward condylar shift of 1.2 mm along the FH plane between stages I and II, which was statistically significant ($p < 0.05$). When stage I was compared with stage III, a 0.9 mm of net linear forward displacement of the c-CH along the FH plane was found. Measurement from c-EAM to the c-PGS also revealed an overall statistically significant result ($p < 0.05$). The linear measurements showed a forward remodeling of the PGS by 0.9 mm between stages I and II which was statistically significant ($p < 0.05$). When stages I and III of treatment were compared, a 1.3 mm of net linear forward remodeling of the PGS after 28 months of functional and fixed appliance therapy was recorded, which was statistically significant ($p < 0.05$).

Table 5. **Comparison of glenoid fossa angle in the total sample (n = 12)**

Pre-treatment (in degrees)†	Post-functional (in degrees)†	After 2nd phase therapy (in degrees)†	*p* value	Significance
83.9 ± 8.52	84.2 ± 11.65	82.3 ± 12.59	0.558	NS

NS, not significant.
† Values in mean ± SD.

Table 6. **Changes in linear measurement from the c-EAM to the c-CH and to c-PGS (n = 12)**

Variables	Pre-treatment (in mm)†	Post-functional (in mm)†	After 2nd phase therapy (in mm)†	Net forward displacement (in mm)††	*p* value	Significance
Centre of condylar head	12.6 ± 0.88	13.8 ± 0.80	13.5 ± 0.59	0.9	0.001	*
Postglenoid spine	5.5 ± 0.62	6.4 ± 0.63	6.8 ± 0.49	1.3	0.001	*

NS, not significant; $*p < 0.05$.
†Values in Mean ± SD
††Values in Mean

Discussion

Glenoid fossa remodeling has been studied after condylectomy (54, 55), condylar fractures (56, 57), TMJ surgical procedures (58), permanent tooth loss (59) and occlusal equilibration (60). Studies have documented the adaptive mechanism of the TMJ in animals following mandibular advancement histologically (5–19, 61–63), through the altered levels of biochemical messengers (64–66) and through altered gene expression (67–70). Human radiographic (71, 72) and MRI (41–50, 73–80) studies confirm the findings of TMJ adaptation to functional displacement of condyles.

MRI is a non-invasive, non-ionizing radiation imaging technique which provides an accurate in-depth assessment of both the hard and the soft tissues (38, 39). Studies have reported sensitivity and specificity of sagittal MRI images to vary between 0.80–0.87 (81–83) and 0.63–0.80 (81, 84), respectively, in the identification of disc displacements while the accuracy has been reported to be 95% (85). Schwaighofer et al. (84) and Tasaki and Westesson (85) found that diagnostic efficacy improved when coronal and sagittal images were combined. Watson et al. (86) and Katzberg et al. (83) found that MRI is a reliable technique for the assessment of hard tissues of TMJ. Liedberg et al. (87) and Westesson (88) concluded that MRI seems to be the method of choice for imaging the soft and hard tissues of TMJ, respectively. However, a recent study (89) evaluating the diagnostic and therapeutic efficacy (90) of MRI in the diagnosis of degenerative and inflammatory TMJ disorders concluded that current evidence is insufficient to conclusively prove the efficacy of MRI. Nevertheless, MRI continues to be a valid clinical diagnostic aid and is commonly used for evaluation of TMJ.

In the present study, visual evidence of change in the shape of the CH, seen in eight of the 12 cases, was quite remarkable. Similar findings have been reported in previous MRI studies (45, 80). Loss of the normal flat contour of posterior part of the CH at the post-functional stage of treatment could perhaps be attributed to proliferation of condylar cartilage in the area. Ruf and Pancherz (80) observed areas of increased MR signal intensity in the posterosuperior aspect of CH which was interpreted as evidence of cartilaginous proliferation. Histological animal studies have also documented proliferation of the condylar cartilage in the posterior and posterosuperior region of CH (5, 8–12, 18–21). The reappearance of flat contour on the posterosuperior surface of the head of condyle at stage III was remarkable. This flattening of condylar contour, which resembled the pre-treatment contour, seems to be an adaptive process both for the proliferated tissues of the CH and those of the retrodiscal area. This finding seems to be in contrast to the previous radiographic (71) and MRI (91) studies, which documented double contours persisting into adulthood. Paulsen and Karle (92) reported new bone formation in the distocranial part of CH following Herbst appliance therapy and the new bone formed was found to be stable after 2 years.

In the present study, areas of increased signal intensity or the presence of double contours were not detected, which could be attributed to either choosing a different MRI sequence, or, perhaps the MRI scans were recorded at a time when such changes had become too innocuous to be visible; but the changes in the condylar morphology were obvious and remarkable. Our findings are also supported by findings of Ruf and Pancherz (91) who reported absence of double contours in adolescents after Herbst treatment which, however, were prominent in young adults (mean age:

16 years). Chintakanon et al. (50) also could not find any double contours in the C-GF complex after 6 months of Twin Block therapy in 10–14-year-old children.

The loss of the anterior notch on the CH has not been reported in previous MRI studies. Our findings are consistent with the histological findings of McNamara and Carlsson (5) and Woodside et al. (19) who reported resorption on the anterior surface of the CH below the area of insertion of the lateral pterygoid muscle after functional mandibular advancement in monkeys. The loss of notching could perhaps be attributed to the reduction in functional stimulation of that region due to reduction in tension generated by the lateral pterygoid muscle (LPM) which attaches to the area. Chintakanon et al. (50), in a clinical study, also showed that there was a reduction in LPM activity in their Twin Block group after 6 months, wherein the Twin Block group retained similar maximum protrusive force while protrusive force increased in the untreated control group. Interestingly, in our study, at the conclusion of treatment, the notch on the CH reappeared and resembled its pre-treatment contour. This might, presumably, be related to normalization of activity of the LPM, directly or indirectly, which remains to be investigated. McNamara and Carlsson (5) also observed that the changes in the tonic activity of the LPM might be, directly or indirectly, correlated to the gradual skeletal adaptations of the skeletal structures (C-GF complex) that resulted from the experimental procedures.

It has been claimed that, in mandibular retrognathia, the condyles are distally positioned as a result of forward head posture.(93) In our study, anterior condylar position in the glenoid fossa was the most common position before the start of treatment (stage I). The finding is in agreement with Pullinger et al. (52) and Chintakanon et al. (50), who also found that in patients with Class II Division 1 malocclusion, the condyles were generally situated in a more anterior position within the glenoid fossa. After 6 months of functional appliance therapy, a majority of our cases showed a more anterior condylar position within the glenoid fossa. However, at the completion of the second phase of therapy, the condyles showed a tendency to revert to their pre-treatment positions, although the anterior condylar position continued to be the most common position in majority of the cases (eight of 12 cases). These findings are similar to those of Ruf and Pancherz (80) and Kinzinger et al (42–44). Kinzinger et al.(42) concluded that in patients treated with a rigid, fixed functional orthopedic appliance (FMA), both joints returned to a physiologic condyle-fossa relationship post-treatment and the improved occlusion was not achieved at the price of unphysiological repositioning within the TMJ. Our results also showed that the condyles tended to move towards a position of true concentricity within the glenoid fossa at the end of the two-phase therapy with functional and fixed appliances.

In response to forward advancement of the mandible, which leads to the condyle being positioned to almost the crest of the articular eminence after insertion of the functional appliance, resorption and flattening of the eminence may be expected as an adaptive mechanism. In the present study, the eminence angle did not change significantly during the course of treatment. These findings are supported by Chintakanon et al. (50), who also did not find any statistically significant change in eminence angle following Twin Block therapy for 6 months. Kuroe and Ito (94) suggested that remodeling in the glenoid fossa is less obvious than the remodeling at the condyle. Ruf and Pancherz (80) also observed that, in most subjects, the amount of the glenoid fossa remodeling was smaller than the amount of condylar remodeling.

The articular disc is considered to be in a normal position in the glenoid fossa when the posterior band of the disc is situated between 11 and 1 O'clock positions, with respect to the superiormost aspect of the CH. However, the normal 12 O' clock position varies with the reference line taken. In the present study, the posterior band of the disc was found to be situated between 11 and 12 O'clock positions at pre-treatment, in respect to the PC line, and between 12 and 1 O'clock positions in respect to the FH plane. During the total course of treatment, the position of the articular disc remained between the 11 and 1 O'clock positions, with respect to both the reference lines. Thus, it could be argued that functional appliance therapy does not cause pathological displacement of the articular disc. These findings are supported by Pancherz et al. (45) and Chintakanon et al (50). Ruf and Pancherz (41) also documented posterior displacement of the disc within physiologic limits after functional appliance therapy. Our data also reveals that the disc appeared to move posteriorly relative to the condyle after functional appliance therapy but approached its pre-treatment position at the end of phase of fixed appliance therapy. These findings are similar to those of Ruf and Pancherz (41) and Kinzinger et al. (42) who found that the disc assumed a retrusive position after insertion of the functional appliance but came back to its pre-treatment position after removal of the appliance. Franco et al. (46) concluded that disc position was not affected by Frankel therapy. Aidar et al. (95) reported a slightly retrusive but physiologic disc position after Herbst therapy. In contrast to the above studies, Foucart et al. (73) found that mean position of the posterior band of the disc was located anteriorly after treatment with Herbst appliance and concluded that Herbst appliance might have induced derangement in 23.3% of their cases.

Anterior repositioning of the condyle in the glenoid fossa caused by insertion of a functional appliance leads to production of stretch in the retrodiscal tissues which, in turn, may cause either stretching of the disc or a posterior displacement of the entire disc. In our study, we found that the change in the position of the anterior band of the disc followed that of the posterior band. Thus, it could be argued that the articular disc was displaced in toto during therapy and did not lose its morphology due to the tension produced by the stretched retrodiscal tissues. This finding also suggests that functional appliance therapy does not lead to alteration of the shape or morphology of the articular disc.

When evaluated in the coronal section, the position of the disc did not change with therapy. In our sample, nine patients had a centrally positioned disc over the condyle, two patients had a laterally displaced disc and one had a medially displaced disc. Overall, in our study, functional appliance treatment seemed to have little effect on the coronal disc position during 28 months of the two-phase therapy. The findings are similar to those of Chintakanon et al. (50), who reported that Twin Block therapy had little effect on coronal disc position. In contrast, Foucart et al. (73) found lateral disc displacement in three of their 15 cases after treatment with Herbst appliance.

Temporal bone adaptation to experimental mandibular advancement has been extensively reported in animal studies (19). Ruf and Pancherz (80) documented anteclination of the PGS following Herbst treatment in children. Thus, a change in not only the anterior but also the posterior slope of the glenoid fossa might be expected, which may lead to change in the glenoid fossa angle. In our study, no statistically significant changes in glenoid fossa angle could be found.

It has been shown that the natural direction of growth of the glenoid fossa, in respect to cranial base structures, is downward (96–99) and backward (96–98). Buschang and Santos-Pinto (97) found that the glenoid fossa, in growing humans, grew backward between 1.8 and 2.1 mm over a 4-year period. Proffit et al. (99) documented that the glenoid fossa usually moves straight down with growth and, occasionally, downward and backward. Histologic studies on monkeys (5, 19, 61) also concluded that normal pattern of remodeling of the PGS involves bone resorption along anterior surface and deposition along the posterior surface. Indeed, a backward growth trend of the glenoid fossa would favour the skeletal Class II malocclusion. It has been proposed that this natural vector of growth, found in both human (96, 97) and non-human primates, may be restricted/altered by the use of functional appliance therapy. Voudouris et al. (100) contended that posterior growth restriction at glenoid fossa might contribute further to the overall anterior position of the glenoid fossa. This would be in addition to any anterior growth modification. The aim of our metric measurements was to find out whether the glenoid fossa did actually shift anteriorly from its pre-treatment position after functional and fixed appliance therapy, or, did the condyle move back within the glenoid fossa. For this, we took the reference landmark to be the c-EAM. As the growth of the EAM is nearly complete by the age of 6 years (101), its centre could be taken as a stable reference landmark. Also, because the shape of EAM may change with age from round to oval and its diameter is known to decrease with age (102), we chose to use the constructed centre of the meatus as it would be least affected by the above mentioned changes in shape.

In our study, we found anterior displacement of the PGS by 1.3 mm along the FH plane, which could be interpreted as evidence of forward remodeling of the glenoid fossa following functional appliance therapy. These findings are similar to those of Vodouris et al. (100), who documented 0.8–1.2 mm of new bone formation in the glenoid fossa after 6 weeks of Herbst therapy in monkeys. Thus, the anteroinferior relocation of the glenoid fossa, as reported in literature, to meet the demands of forward mandibular positioning induced by the functional appliances, seems to be one of the mechanisms involved in correction of Class II malocclusion following functional appliance therapy. It is interesting to note that, although small, the tendency for anterior remodeling of PGS continued in the fixed phase of treatment.

The present study infers that the internal anatomic arrangements of the TMJ and the condyle glenoid fossa relationship, which are significantly altered during the phase of functional appliance therapy, move to acquire a relationship which is close to the pre-treatment relationship, or, in other words, a normalization of altered relationship occurs during the second phase of therapy which is aimed to maintain and stabilize the changes produced by the functional appliances. This study highlights with greater evidence, on the basis of MRI, that the C-GF complex assumes an anterior position in the craniofacial complex while the internal anatomic arrangement within the TMJ complex normalizes to pre-treatment position after functional appliance therapy.

A major limitation of the study design was the small sample. Nevertheless, the findings are obvious and significant. These findings should be confirmed in future studies on a bigger sample size. A larger sample would also help to identify the possibility of sexual dimorphism, which could not be addressed in our study. Another area of concern was the lack of controls in our study design, which could not be addressed due to ethical constraints.

It is proposed that future studies on functional appliances should concentrate more on glenoid fossa and temporomandibular joint remodeling, and specifically, positional change of the glenoid fossa. The study also highlights the need for the development of precise protocols for evaluation of the MRI of TMJ. Future research should focus to develop some simpler but more accurate radiologic markers or methods, such as 3-D CBCT, which would allow easier superimposition of cephalometric images and MRI scans.

Conclusions

1. The condylar position shifted anteriorly within the glenoid fossa after functional appliance therapy but tended to assume a concentric position at the completion of fixed appliance therapy.
2. The eminence angle did not change significantly after 28 months of two-phase therapy with functional and fixed appliances.
3. The articular disc shifted posteriorly relative to the CH after functional appliance treatment but tended to approach its pre-treatment position at the completion of treatment.
4. The coronal disc position remained unaffected after the two-phase therapy with functional and fixed appliances.
5. The PGS remodeled and assumed a forward position by 1.3 mm after 28 months of the two-phase therapy.
6. There was no clinical or MRI evidence of development of any pathological changes in the C-GF complex during the two-phase therapy with functional and fixed appliances.

Clinical relevance

The mechanism of skeletal Class II correction with functional appliances has long been debated. Functional appliances act through a variety of mechanisms, one of which is anterior relocation of the C-GF complex. This view is supported by a number of animal studies and only a few human studies. The current MRI study on removable functional appliances followed by fixed appliance therapy supports and provides evidence for anterior remodeling of the condyle-glenoid fossa complex.

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