ORIGINAL ARTICLE

Improved clinical use of Twin-block and Herbst as a result of radiating viscoelastic tissue forces on the condyle and fossa in treatment and long-term retention: Growth relativity

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Understanding mechanisms of action for orthopedic appliances is critical for orthodontists who hope to treat and retain the achieved corrections in patients with initial Class II mandibular retrognathism. That knowledge can help orthodontists produce clinically significant bone formation and avoid compression at the condyle-glenoid fossa region. It also assists us to understand the differences between short-term and long-term treatment results. It was previously thought that increased activity in the postural masticatory muscles was the key to promoting condyle-glenoid fossa growth. By analyzing results from several studies, we postulate that growth modification is associated with decreased activity, which leads to our *nonmuscular* hypothesis. This premise has its foundation on 3 key specific findings: significant glenoid fossa bone formation occurs during treatment that includes mandibular displacement; glenoid fossa modification is a result of the stretch forces of the retrodiskal tissues, capsule, and altered flow of viscous synovium; observations that glenoid fossa bone formation takes place a distance from the soft tissue attachment. The latter observation is explained by transduction or referral of forces. Evidence is presented, therefore, that the 3 trigger switches for glenoid fossa growth can similarly initiate short-term condylar growth modifications because the 2 structures are contiguous. These are displacement, several direct viscoelastic connections, and transduction of forces. Histologic evidence further shows that stretched retrodiskal tissues also insert directly into the condylar head's fibrocartilaginous layer. The impact of the viscoelastic tissues may be highly significant and should be considered along with the standard skeletal, dental, neuromuscular, and age factors that influence condyle-glenoid fossa growth with orthopedic advancement. These biodynamic factors are also capable of reversing effects of treatment on mandibular growth direction, size, and morphology. Relapse occurs as a result of release of the condyle and ensuing compression against the newly proliferated retrodiskal tissues together with the reactivation of muscle activity. To describe condyle-glenoid fossa growth modification, an analogy is made to a light bulb on a dimmer switch. The condyle illuminates in treatment, dims down in the retention period, to near base levels over the long-term. (Am J Orthod Dentofacial Orthop 2000;117:247-66)

According to Aristotle, to be successful in theorizing is to realize the highest excellence,[1] for practical applications. The purpose of this article is to improve dentofacial orthopedic treatments by describing a specific, nonmuscular hypothesis that explains histologically the way the condyle modifies beyond the level that can be explained by displacement alone (Fig 1). As orthodontists pursue more ambitious treatments for their patients with mandibular retrognathism, they are increasingly turning to orthopedic appliances such as the Herbst, Twin-block, and other auxiliaries.[2-4] Part of the rationale is to augment edgewise appliances with fixed intermaxillary elastics and coils, although it has been reported that these edgewise systems also produce condylar growth modification.[5] Some claim orthopedic appliances assist in the growth of mandibles and promote their use in this manner. As a responsibility to our patients to achieve the highest standards of treatment possible, we need to understand exactly why and how those appliances work.

"Can we aid in the growth of condyles to a clinically significant degree?" This commonly asked question must always be qualified in terms of time before being answered intelligently. This is because the clinically significant results of short-term treatment[6] have been shown to be quite different from the findings on long-term stability.[7]

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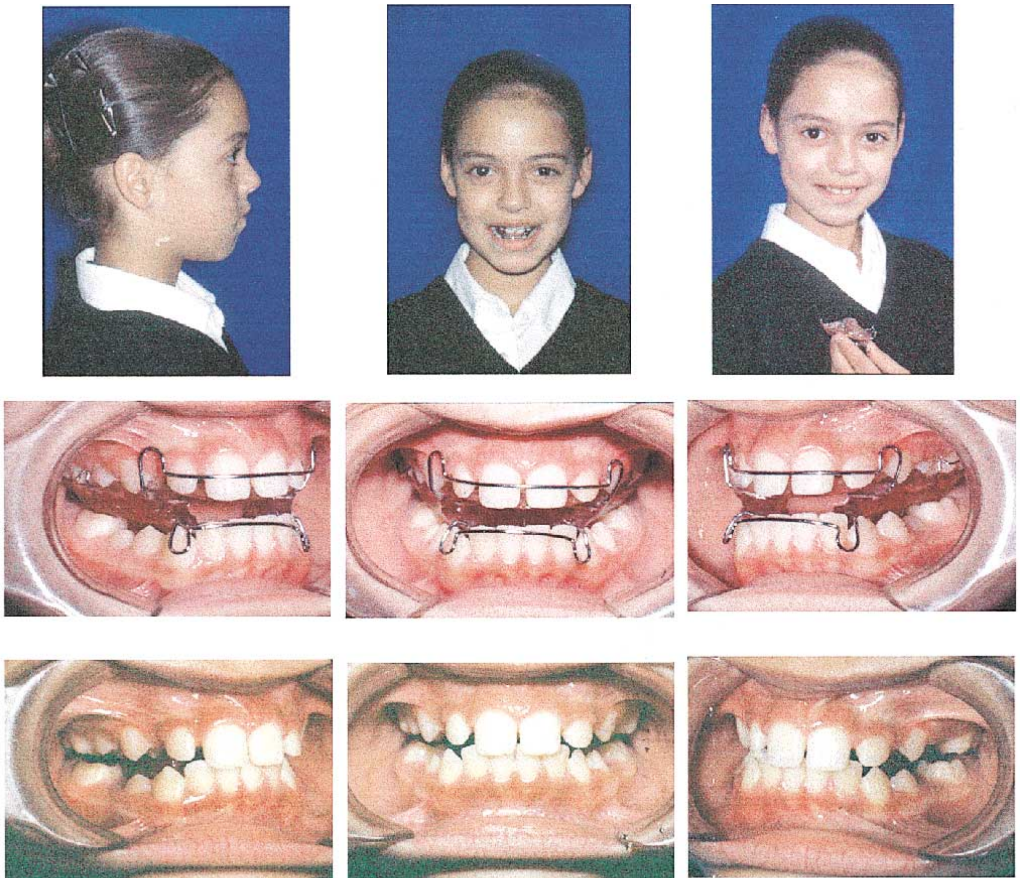


Fig 1. A, Transfer patient age 10 with a functional appliance to improve mandibular retrognathism and the vertical dimension with the use of mandibular anterior displacement. Immediately after appliance removal, the mandible is artificially positioned forward with minimal posterior dental contacts. Orthodontic recall appointments reveal this is not mandibular growth stimulation but rather temporary anterior positioning of the condyles in the fossae.

It is important to differentiate between 3 conditions that often overlap: normal condyle-glenoid fossa (C-GF) growth, orthopedic remodeling as a result of condylar advancement, and pathosis at the condyle. Pathologic adaptations[8,9] show the C-GF region's ability to be modified significantly[10] (Fig 2). This type of growth is distinctly different from the limited short-term growth modification observed with orthopedic displacement therapy.[11-20]

Interpreting literature on C-GF modification can be challenging, mainly because of the variation in the study designs, analyses, range of orthopedic appliances used, and compliance.[21] A literature overview (Table I) classifies studies with continuous versus intermittent orthopedic displacement of the condyle and distinguishes between those conducted on animals and human beings.

HOW CONDYLAR MODIFICATIONS OCCUR

Over the years, several theories have emerged attempting to shed light on condylar growth. One of the earliest theories, the *genetic* theory, suggests the condyle is under strong genetic control like an epiphysis that causes the entire mandible to grow downward and forward.[22] Although this may be related more to development of the prenatal than postnatal condyle, the theory does indirectly question the effectiveness of orthopedic appliances in condylar growth as proposed by Brodie.[23] Several long-term investigations actually showed clinically insignificant condylar growth modification after continuous mandibular advancement with a reasonable retention period in human beings[24,25] although the initial treatment results appeared encouraging.[26] This leads to the conclusion that the general growth of the condyle appears relatively unalterable in long-term studies. In

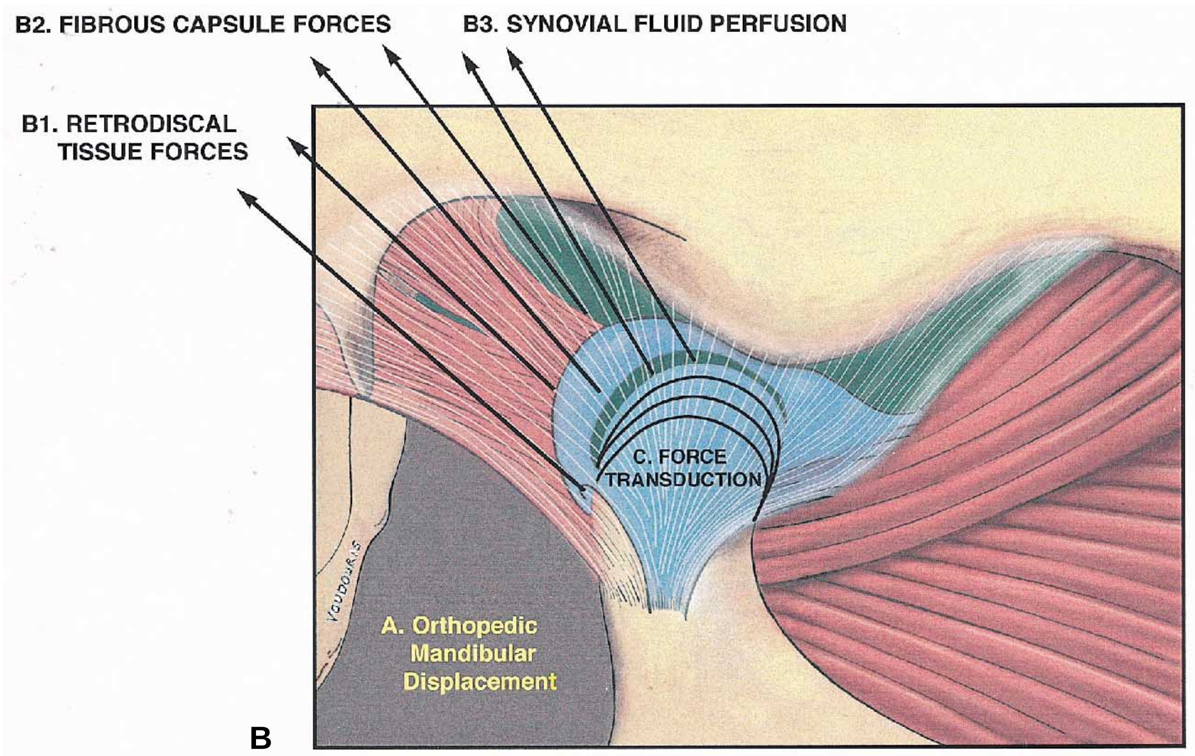


Fig 1. B, Growth relativity hypothesis for condylar and glenoid fossa growth with continuous orthopedic displacement. Three factors influence growth modification: *A*, displacement; *B*, viscoelastic tissue pull (*arrows*); and *C*, transduction with fibrocartilage. Viscoelastic tissues include *B1*, superior and inferior bands of the retrodiskal fibers; *B2*, fibrous capsule (*fine white lines*); and *B3*, synovial fluid perfusion in a posterior direction. The pull of the retrodiskal fibers, capsule, and the flow of synovial fluids on the condyle relative to the glenoid fossa are in a posterosuperior direction. The forces are translated to the condyle with the articular disk's (*blue region*) posterior, anterior, lateral and medial (collateral) attachments.

contrast, one similar study of primates showed significant condylar growth modifications over the long-term but only after retention periods that were far too long to be feasible for human beings.[27]

DEMISE OF THE LATERAL PTERYGOID HYPERACTIVITY HYPOTHESIS[28]

A second hypothesis,[13,29,30] based on the earliest available acute and blind EMG monitoring technique, suggests that hyperactivity of the lateral pterygoid muscles (LPM) promotes condylar growth. Rees[31] reported that other muscles and tendons, including those of the deep masseter and temporalis, also attach to the articular disk region. Attachments of the LPM to the condylar head or articular disk may be expected to cause condylar growth, but anatomic research has not found evidence that significant attachments actually exist (Fig 3). The LPM tendon is observed attaching, however, to the anterior border of the fibrous capsule (Fig 4) that in turn attaches to the fibrocartilage of the condylar head and neck anteriorly. At the same time, it is doubtful that initial hyperactivity could occur where the LPM muscle has been shortened by continuous mandibular displacement therapy. By using LPM myectomy in rats, which may have disrupted condylar blood supply, Whetten and Johnston[32] found little evidence that LPM traction had any pronounced effect on condylar growth. More recently, permanently implanted longitudinal muscle monitoring techniques[33,34] have found that the condylar growth[35] is actually related to decreased postural and functional LPM activity.[36,37] This notion was also supported in human studies by Auf der Maur,[38] Pancherz and Anehus-Pancherz,[39] and Ingervall and Bitsanis[40] that reported decreased muscle activity. The LPM hyperactivity theory brought forward by Charlier et al,[11] Petrovic,[41] and later espoused by McNamara[13,14] however, was important in prompting further investigations in muscle-bone interactions.[42] Petrovic[43] studied the removal of the lateral pterygoid muscles and retrodiskal tissues "condylar frenum" for the effect on condylar growth.

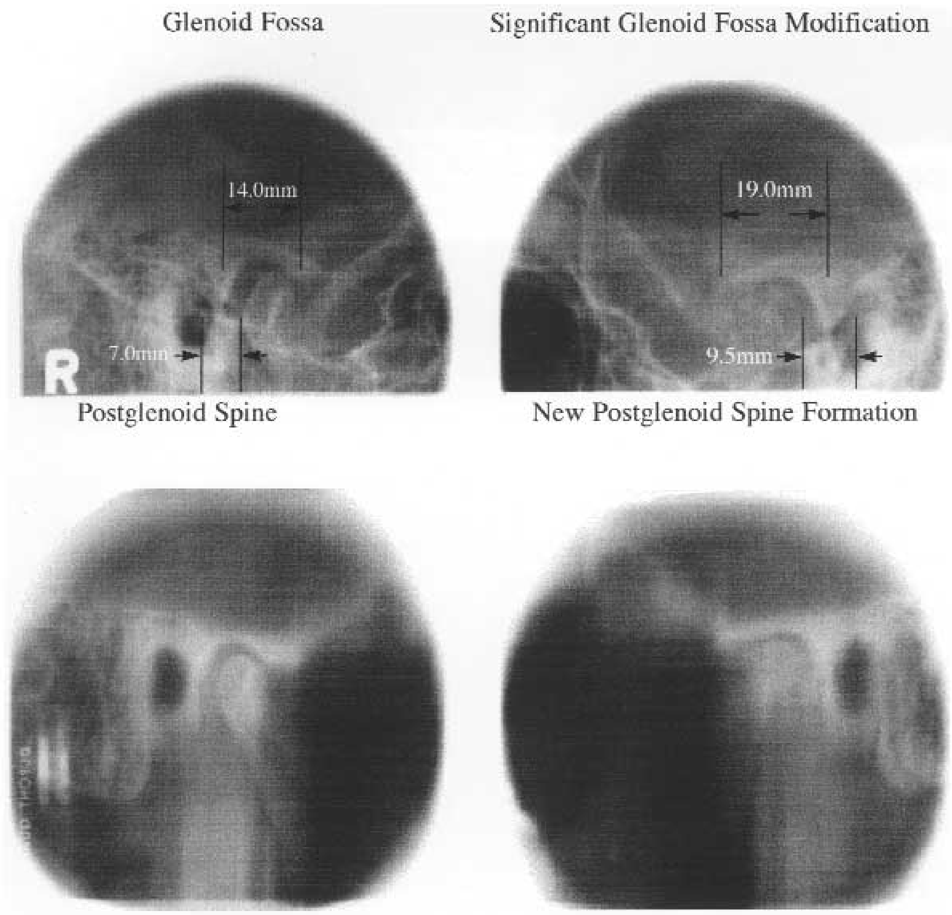


Fig 2. Transcranial views and corrected serial section tomography (*bottom row*) of an otherwise healthy adult female patient's C-GF region pretreatment shows a relatively normal right C-GF region and a left side that has undergone marked adaptation of the glenoid fossa. Clinically significant (>1 mm parallel to the occlusal plane) bone formation of at least 2.5 mm is shown at the left postglenoid spine and resorption at the articular eminence associated with condylar hypoplasia. The left GF adaptation has resulted in both a markedly shallower vertical dimension and wider anteroposterior dimension because of articular eminence remodeling. The condylar osteophyte is partially associated with the altered insertion of the superior head of the lateral pterygoid muscle (SHLP).

WHAT SPECIFICALLY AFFECTS THE GROWTH AT THE CONDYLAR HEAD?

A third hypothesis, the *functional matrix* theory, postulates the principal control of bone growth is not the bone itself, but rather the growth of soft tissues directly associated with it.[44-48] Although this was supported in part by investigations testing the different growth and developmental responses between the condyle[49-51] and epiphysis, there has been no explanation as to exactly how condylar growth would be stimulated. Thus, this theory's validity has been questioned.[28,52] One of the reasons was that there was little explanation of the specific mechanism by which the condyle was stimulated to grow. Endow and Hans[53] presented an excellent overall perspective suggesting that mandibular growth is a composite of regional forces and functional agents of growth control that interact in response to specific extracondylar activating signals. These extrinsic signals are the main focus of this article. They are the foundation of the growth relativity hypothesis.

Growth relativity refers to growth that is relative to the displaced condyles from actively relocating fossae. Growth is discussed relative to long-term retention results, rather than short-term treatment outcomes that are clearly different. Viscoelasticity is conventionally applied to elastic tissue, primarily muscles. In this article viscoelasticity refers to all

Table I. Representative overview of various types of studies of orthopedic effects on condylar advancement*

Effects of continuous displacement on the condyle
Clinical studies
Pancherz 1979
Pancherz and Anehus-Pancherz 1980
Pancherz 1982
Sarnas-Pancherz 1982
Wieslander 1984
Hag and Pancherz 1988
Pancherz and Littmann 1989
Valant and Sinclair 1989
McNamara and Mollenhauer 1997
Pancherz and Fackel 1990
Hansen et al 1990
Pancherz 1991
May et al 1992
Wieslander 1993
Pangrazio-Kulbersh and Berger 1993
Windmiller 1993
Pancherz and Anehus-Pancherz 1994
Jasper et al 1997
Animal studies
Altuna 1979
Woodside et al 1983
Voudouris 1988
Sessle et al 1990
Effects of intermittent displacement on the condyle
Clinical studies
Andreasen 1936
Bjork 1951
Baume 1959
Moss 1962
Thilander and Filipsson 1966
Jakobsson 1967
Trayfoot 1968
Frankel 1969
Charlier et al 1969
Harvold and Vargervik 1971
Algren 1972
Woodside et al 1975
Auf der Maur 1980
Graber LW 1983
Teuscher 1983
Vargervik and Harvold 1985
Thilander and Filipsson 1966
Ingervall and Bitsanis 1986
Clark 1988
Vardimon 1989
Mamandras 1990
DeVincenzo 1991
Livieratos and Johnston 1995
Gianelly 1995
Animal studies
Breitner 1940
Baume 1961
Hiniker and Ramfjord 1966
Lieb 1968
Joho 1968
Charlier et al 1969
Payne 1971
Stockli and Willert 1971
Petrovic and Stutzmann 1972
Adams et al 1972
Elgoyen et al 1972
McNamara 1973
Petrovic et al 1975
Oudet and Petrovic 1975
McNamara 1975
McNamara and Carlson 1979
Stutzmann and Petrovic 1979
Graber TM 1983
Petrovic 1984
McNamara and Bryan 1987
Tsolakis et al 1997

This is a representative sample of studies and is not intended to include all orthopedic investigations.[35]

noncalcified tissues. Specifically, viscoelasticity addresses the viscosity and flow of the synovial fluids, the elasticity of the retrodiskal tissues, the fibrous capsule and other nonmuscular tissues including LPM perimysium, TMJ tendons and ligaments, other soft tissues, and bodily fluids.

VERTICAL DIMENSION INCREASES AND DECREASED LPM ACTIVITY

The examination of soft tissues (fascia and tendons attachments, the perioral muscles of the lips, cheeks, and tongue) has also been undertaken.[54,55] Investigations of active patients with chronic oral respiration[56-58] with resultant skeletal maxillary constriction, together with increased lower vertical face height, showed significant effects caused primarily by disturbances in the equilibrium of soft tissues. In addition to breathing pattern, a possibility of altered salivary flow and not necessarily of muscle activity alone has been implicated. Some studies suggested a form of condylar pull "stress" that resulted in a significant mandibular growth.[59-61] Conversely, condylar compression demonstrated decreased C-GF modification, as shown by Graber[62] and Joho.[63] Interestingly, increases in the vertical dimension have accompanied decreased postural EMG masticatory muscle activity as demonstrated by Storey[64] and others.[65-67] With evidence of decreased muscle activity during the use of propulsive orthopedic appliances, one can ask the question: what is causing the observed growth modifications?

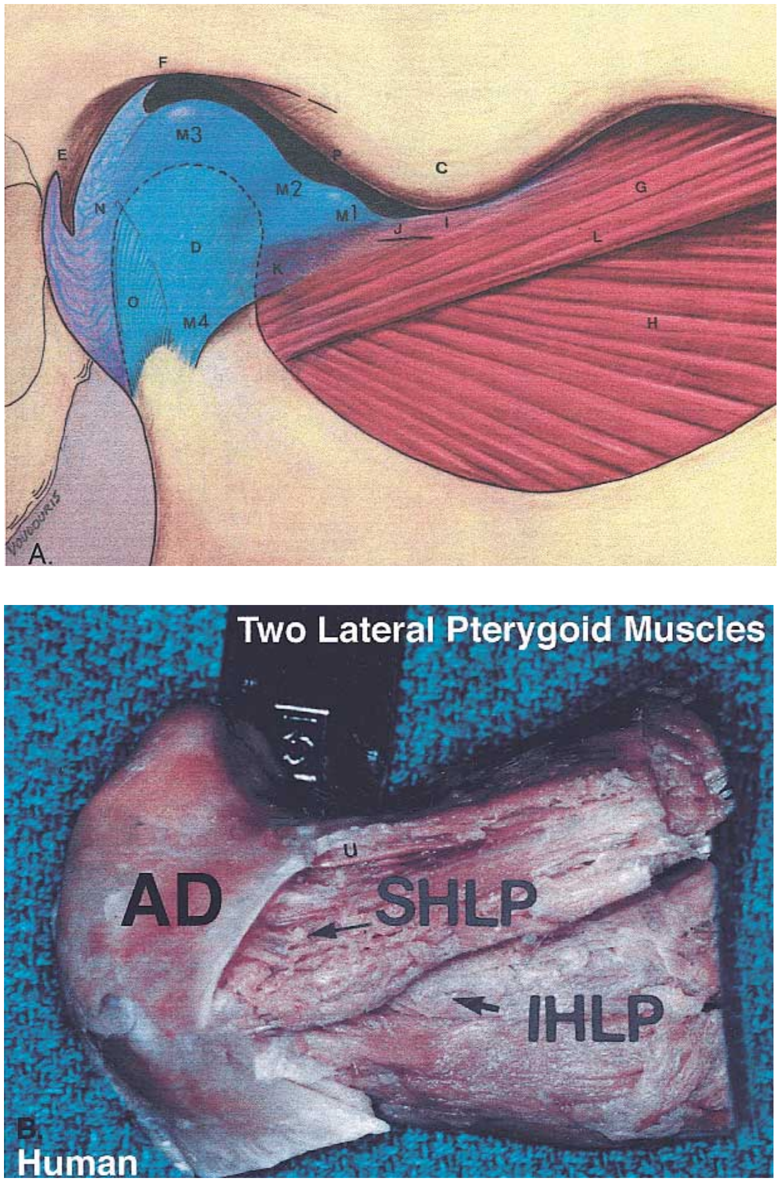


Fig 3. A, Three-dimensional illustration of unadvanced human TMJ shows minimal attachment (*J*) of superior head of the lateral pterygoid muscle to articular disk (*M1, blue*) and retrodiskal tissue complex (*N*). (For other label details, please see reference 35.) **B**, Clean, representative TMJ dissection from human adult cadaver specimen to expose the pterygoid muscles. Fascia and tendon of a small upper proportion (*u*) of SHLP fibers are firmly attached to stabilize the articular disk from the posteriorly attaching retrodiskal tissues that continue to be extended at the start of closing (not shown). It is important to note the majority of both the SHLP and inferior head of the LPM (IHLP) fibers attach lower to the neck of the condyle (*arrows*) and not the articular disk or condylar head.

GROWTH RELATIVITY HYPOTHESIS

Three Main Foundations

The glenoid fossa promotes condylar growth with the use of orthopedic mandibular advancement therapy. Initially, that displacement affects the fibrocartilaginous lining in the glenoid fossa to induce bone formation locally (Fig 5). This is followed by the stretch of nonmuscular viscoelastic tissues. Third and the most interesting aspect is the new bone formation some distance from the actual retrodiskal tissue attachments in

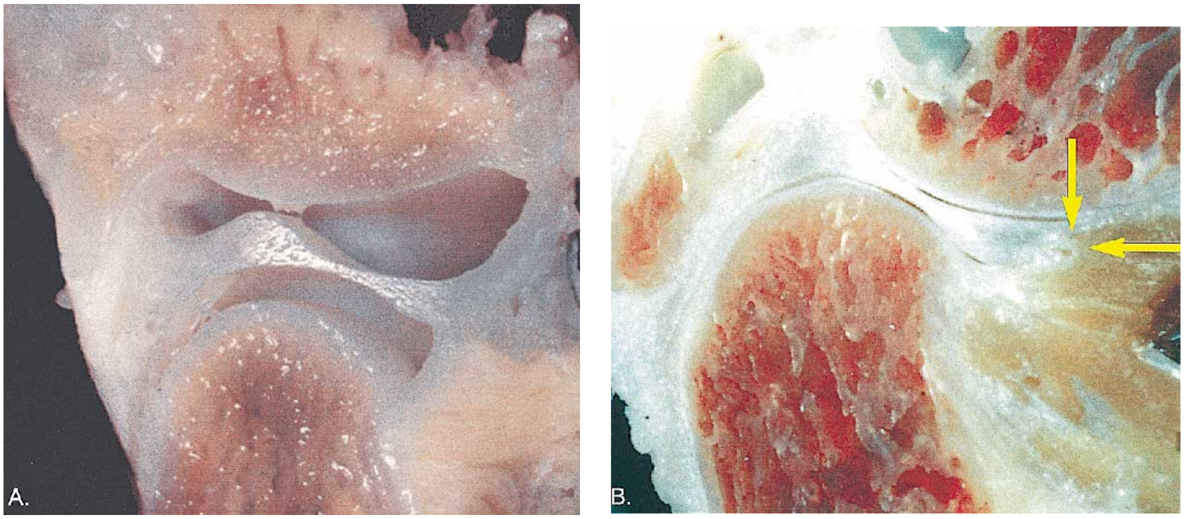


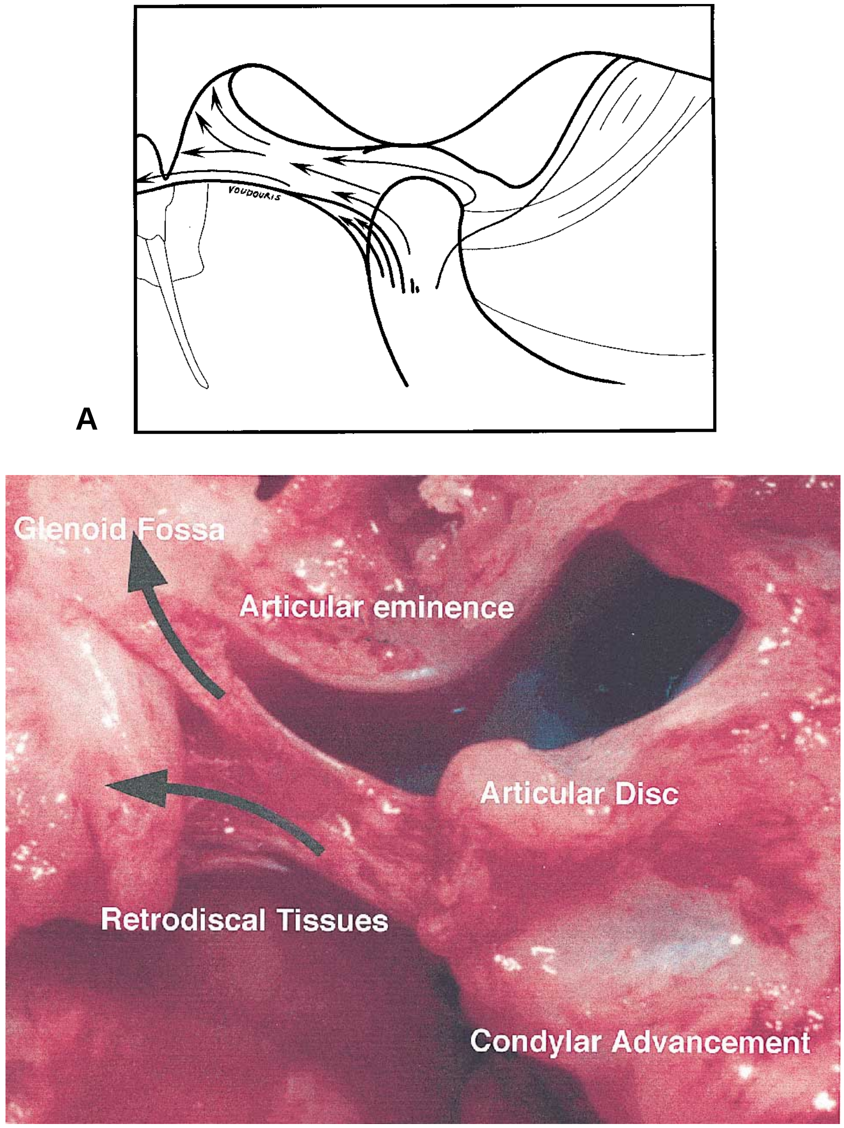
Fig 4. A, Parasagittal, three-dimensional perspective of a primate TMJ that is advanced downward and forward. The SHLP muscle is connected to the anterior aspect of the condylar head by the fibrous capsule. The condylar head is also attached posteriorly by the firm retrodiskal tissues. Note the appearance of viscous synovial fluid and membrane remnants contacting the posterosuperior aspect of the condyle and the superior aspect of the posterior band of the articular disk. The articular disk is similar to a parachute anchored by the anterior and posterior attachments of the fibrous capsule and posterior retrodiskal tissues (the collateral ligament attachments of the articular disk are not shown (see Fig 3*B*). **B**, Sagittal, macroscopic, two-dimensional section of unadvanced *Macaca fascicularis* TMJ that shows, similar to human beings (dissimilar to the rat), minimal association of SHLP muscle and tendon with the articular disk-retrodiskal complex in the closed position (*vertical arrow*). SHLP muscle tendons and fibers begin to insert into the fibrous capsule (*horizontal arrow*) anterior to the lower chamber space and inferiorly into the condylar neck communicating with the fibrocartilage.

the fossa (Fig 6). The glenoid fossa and the displaced condyle are both influenced by the articular disk, fibrous capsule, and synovium, which are contiguous, anatomically and functionally, with the viscoelastic tissues. Therefore, condylar growth is affected by viscoelastic tissue forces via attachment of the fibrocartilage that blankets the head of the condyle (Fig 7*A*).

Microscopic examination of TMJ sections has revealed direct connective tissue attachments of the retrodiskal tissues *into* the unique fibrocartilaginous layer of the condylar head (Fig 7*A*). Interestingly, this highly functional fibrocartilage that caps the condyle in 3-dimensions is not found on epiphyses. There are posterior, anterior (Fig 7*B*), and 2 collateral soft tissue attachments between the retrodiskal tissues (Fig 1*B* and 3) and the condyle, along with the fibrous capsule (Fig 1*B*) and synovial fluid. These distinct attachments to the condylar head use the articular disk and fibrocartilage to communicate between the GF and the condyle. During orthopedic mandibular advancement, there is an influx of nutrients and other biodynamic factors into the region through the engorged blood vessels of the stretched retrodiskal tissues (Fig 7*A*) that feed into the fibrocartilage of the condyle. The expulsion of these factors occurs during reseating of the displaced condyles in the fossa during relapse. The result is a metabolic pump-like action of the retrodiskal tissues.[68]

Another promising area of investigation is the alteration of synovial fluid dynamics that occurs with orthopedics. Nitzan[69] used disoccluding appliances in human beings to demonstrate low subatmospheric intra-articular pressures within the TMJ in the open position. The low intra-articular pressures were significant in altering the joint fluid dynamics or flow of synovial fluid.[70] It was observed surgically that these negative pressures shift synovial fluid perfusion in a posterior displaced direction. This TMJ pump may initially act similar to a suction cup placed directly on the displaced condylar head to activate growth (Fig 5*A*). These negative pressures, initially below capillary perfusion pressures, permit the greater flow of blood into the C-GF region (Fig 7*A*). This increases the flow to the synovial capillaries near the condyle and the fossa.[71] Surprisingly, significant sex differ-

A



B

Fig 5. A, Three-dimensional perspective illustrates the growth relativity hypothesis in the orthopedically advanced condyle. The posterior, anterior, and lateral attachments of the retrodiskal-articular disk complex are shown. The condyle may be guided upward and backward by these and other attachments. The retrodiskal-articular disk complex is pulled in the opposite direction of the arrows for glenoid fossa modification. The altered dynamics of the clear, viscous synovial fluid that perfuses posteriorly in the small lower TMJ chamber may facilitate growth beneath the hydrophilic condylar fibrocartilage. In the upper chamber, the opposing anterior flow of synovial fluids may similarly influence GF growth. **B**, Sagittal surgical examination of a primate TMJ advanced anteriorly shows extended superior meniscotemporal ligament of the retrodiskal tissues for posterosuperior force on the articular disk-condylar complex. The inferior mandibulotemporal lamina of the retrodiskal tissues anchored to the postglenoid spine (*lower arrow*) also demonstrates tissue extension applied *directly* to the condyle. The lateral pterygoid muscle lengths anterior to the articular disk are shortened due to the continuous advancement.

ences were found with females generating greater intra-articular pressures than males.

Wolff's law[72] states that bone architecture is influenced by the neuromusculature. This law may now be extended for the orthopedically displaced condyle. With orthopedic advancement of the mandible, the law of Growth Relativity states that bone architecture is influenced by the neuromusculature and the contigu-

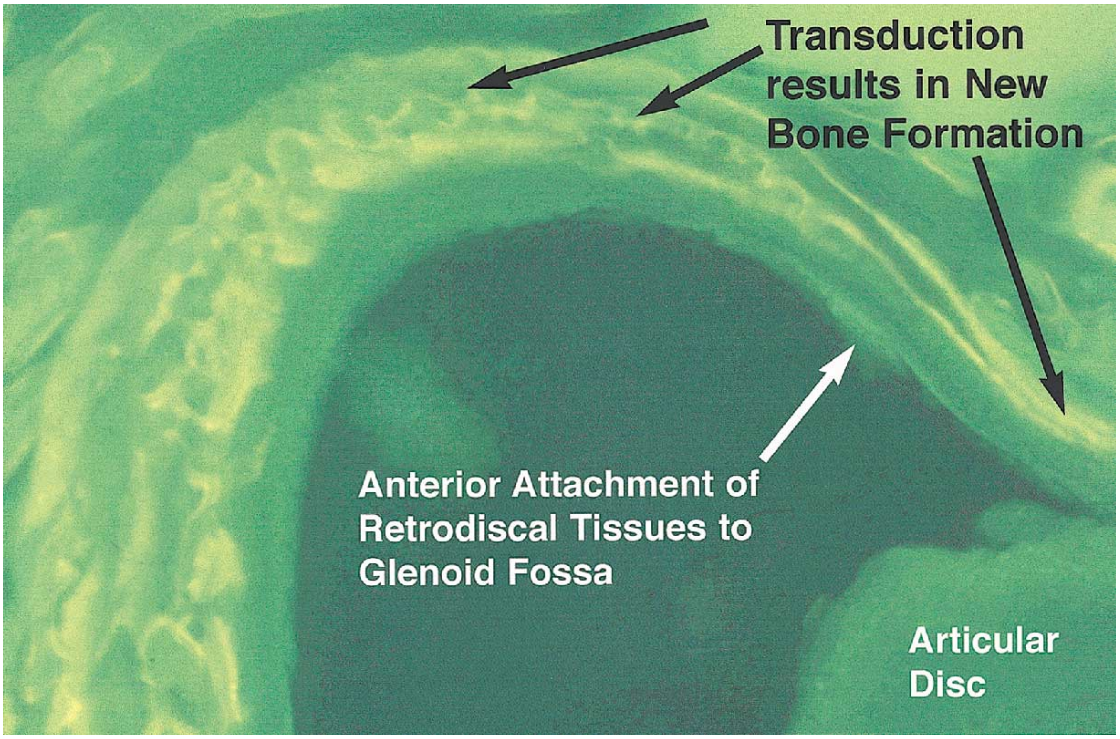


Fig 6. Transduction: photomicrograph of undecalcified parasagittal section of the glenoid fossa where the condyle was orthopedically advanced for 12-weeks. (Tetracycline vital stain; original magnification ×3; fluorescence microscopy.) Retrodiskal tissues (not shown) attach near the petrotympanic fissure and extend toward the most anterosuperior end of the attachment (*white arrow*). It is important to observe, however, that the new bone formation extends a large distance *beyond the actual attachment* of the retrodiskal tissues toward the height of the articular eminence (*right black arrow*) demonstrating transduction or referral of force.

ous, nonmuscular, viscoelastic tissues anchored to the glenoid fossa and the altered dynamics of the fluids enveloping bone.

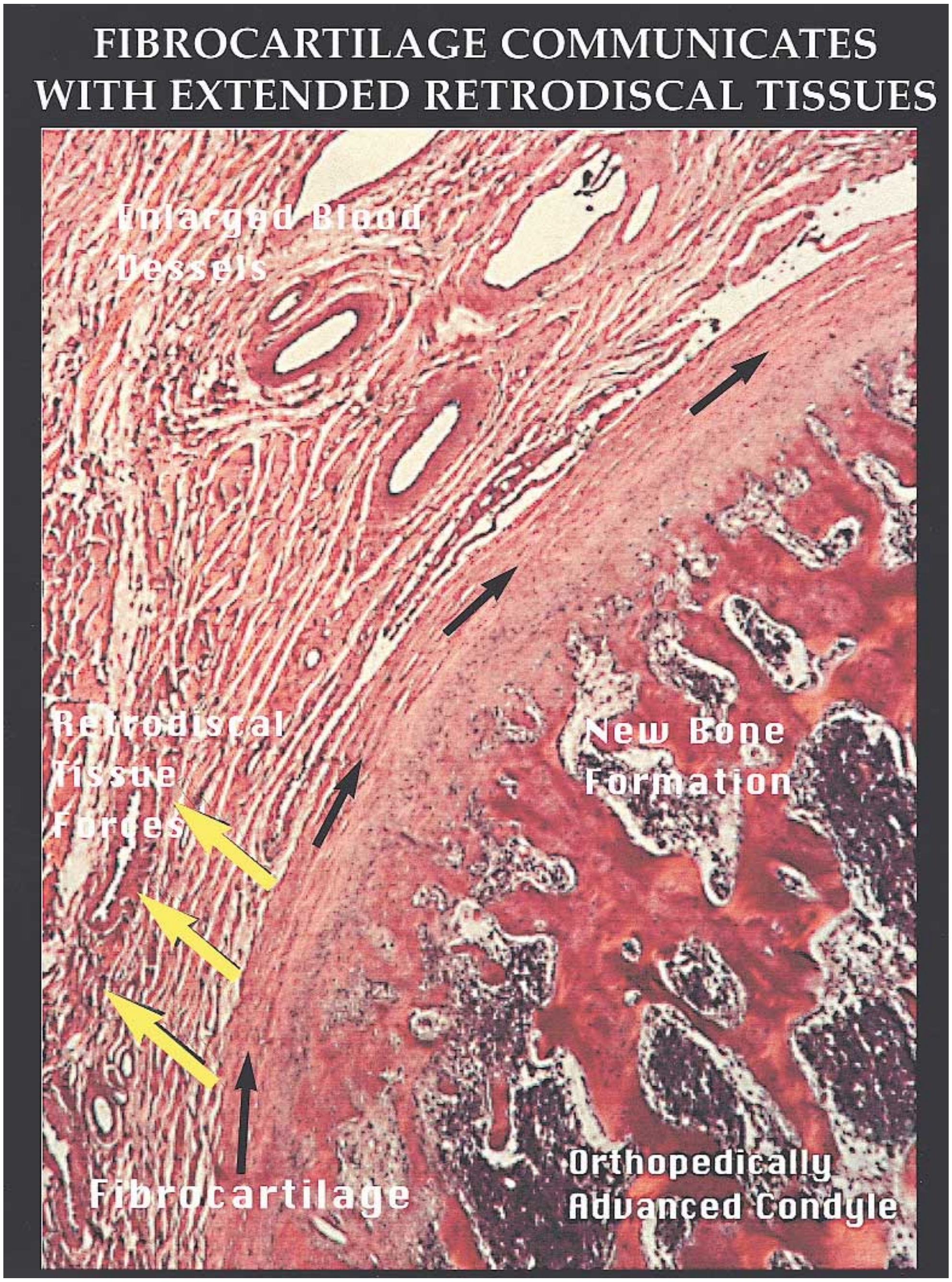
THREE GROWTH STIMULI

Displacement + Viscoelasticity + Referred Force

The concept that viscoelastic tissue forces can affect growth of the condyle suggests that modification first occurs as a result of the action of anterior orthopedic displacement. Second, the condyle is affected by the posterior viscoelastic tissues anchored between the glenoid fossa and the condyle, inserting directly into the condylar fibrocartilage. Finally, it is hypothesized that displacement and viscoelasticity further stimulate (or turn on the light switch for) normal condylar growth by the transduction of forces over the fibrocartilage cap of the condylar head (Fig 7*A*). The ensuing increase in new endochondral bone formation appears to radiate as multidirectional finger-like processes (Fig 7*A*) beneath the condylar fibrocartilage, and significant appositional (periosteal) bone formation is seen in the fossa (Fig 6). Condylar growth is also mediated by other intrinsic and extrinsic biofeedback factors that are present and active even when the mandible is not distracted.[29,42]

GROWTH RESTRICTION OF THE GLENOID FOSSA

Cephalometric investigations by Bjork[73] and Popovich and Thompson[74] in healthy patients from the Burlington Growth Center, among other facilities, have found that the glenoid fossa grows in a posterior and inferior direction. In addition, the anterior slope of the articular eminence undergoes extensive resorption in a posterior and inferior direction[75] and the posterior slope undergoes compensatory endosteal deposition until 7 years of age. The condyles and fossae in individuals with average FMA grow generally in a posterior and inferior direction based on the cranial base superimposition.[76] That means the posteriorly directed forces of the viscoelastic tissues may affect the advanced condyle and fossa at a time when the glenoid



A

Fig 7. A, Photomicrograph of decalcified parasagittal section of an orthopedically advanced condyle for 12 weeks. (Hemotoxylin-eosin stain; original magnification ×10; nonpolarized light.) Posterior biophysical communication with the condylar head is demonstrated where the retrodiskal fibers actually insert and pull directly on the fibrocartilage of the condyle (*yellow arrows*). This is an independent communication since the inferior lamina of the retrodiskal fibers attaches directly to the fibrocartilage under the posterior band of the articular disk and may be a unique histologic finding (personal communication, Tom Graber, May 1999). Fibrocartilage acts as a conduit (*black arrows*) for transduction of forces at both the fossa (Fig 6) and condyle for growth modification.

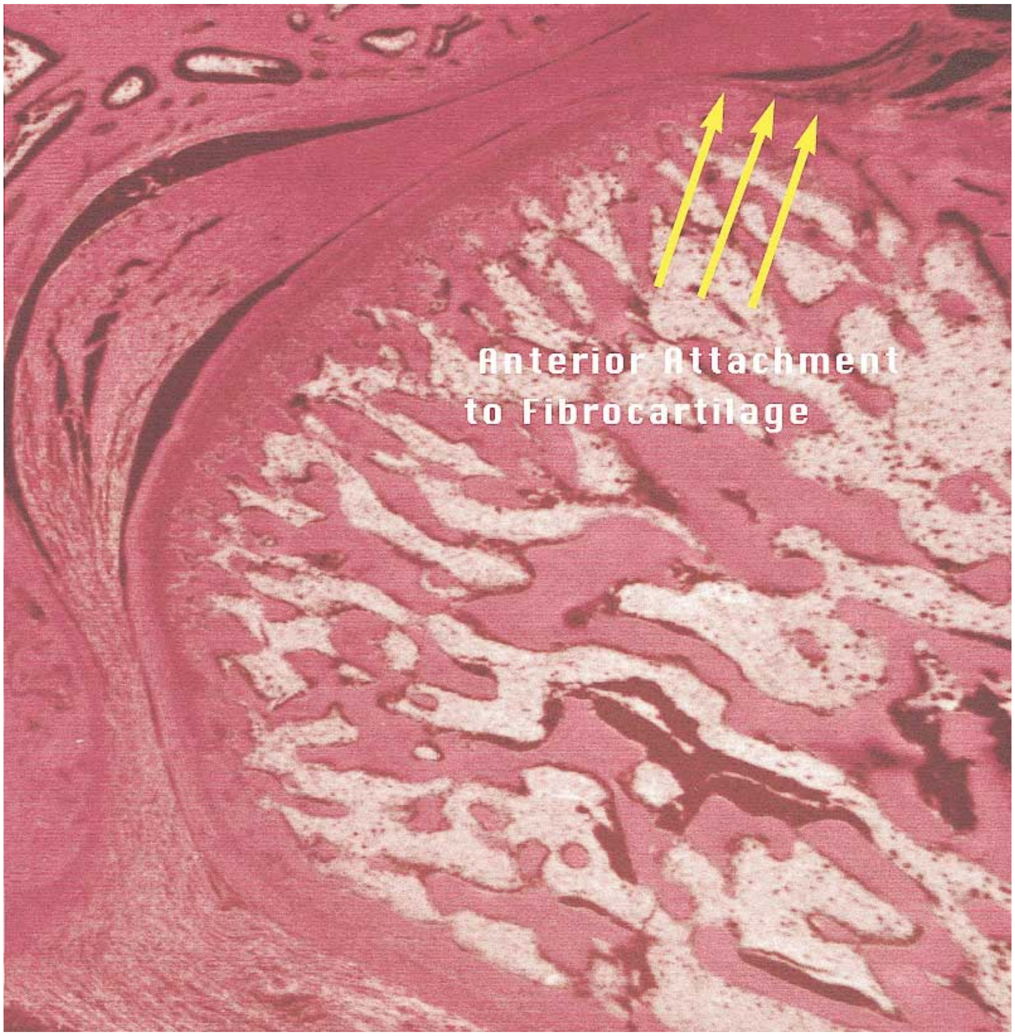
B


Fig 7. B, Photomicrograph of a decalcified parasagittal section of the TMJ. (Hematoxylin and eosin; original magnification ×10.) The indirect anterior communication of the retrodiskal fibers with the fibrocartilage of the condyle is dependent on the articular disk, anterior fibrous capsule, and peri-mysium of the SHLP muscle. Additional communications include the deep masseter and temporalis. These 3 intermediary connective tissues *(arrows)* are used to communicate with the fibrocartilage of the condylar head.

fossa should actually be moving naturally in a posteroinferior direction.

However, the fossa is reported to grow in the reverse direction, relocating anteroinferiorly to meet active condylar modification and to restore normal function during orthopedic treatment. This is a relative restriction of normal fossa growth, and it contributes toward Class II correction. Growth restriction of the GF can be particularly useful when it is combined with restriction of the maxillary growth while the mandible grows downward and forward.[28] In healthy patients, the horizontal growth component of the brain,[77] which is in close proximity to the glenoid fossa, has been suggested to cause the fossa to be displaced posteroinferiorly relative to the condylar growth. Unfortunately, this theory has not yet been adequately proven experimentally.

Modification of the GF can be clinically significant whenever the 2 structures, the condyle and the fossa, are separated. In young growing subjects, reciprocal forces of the viscoelastic tissue between the fossa and the condyle can change C-GF growth directions to our advantage (Fig 8*A*). This growth appears to be limited by the amount of mandibular advancement, proliferation, and turnover of retrodiskal tissues. Experimental

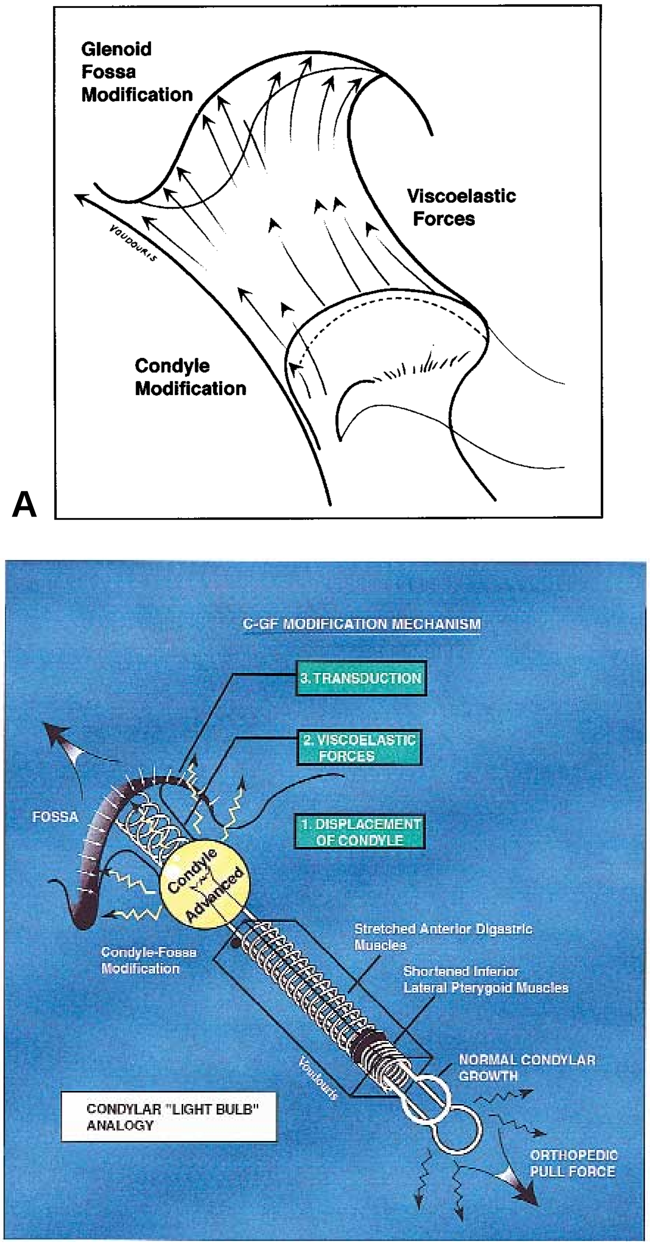


Fig 8. A, Illustration of a ¾ anterior-lateral perspective of the forces on the advanced condyle and glenoid fossa through their respective soft tissue attachments that change their growth directions. They are part of at least 6 viscoelastic lines of communication including synovial fluid and the fibrous capsule that have been found to connect directly and indirectly with the interfacing fibrocartilaginous layer of the condyle. The sixth attachment to the condyle is specifically through the more diagonally oriented posterior and middle fibers of the fibrous capsule overlaying and communicating not only with the condyles but also with the retrodiskal-articular disk complex (see Fig 1*B*). **B**, Light bulb analogy of condylar growth and retention. When the growing condyle is continuously advanced, it lights up like a light bulb on a dimmer switch. When the condyle is released from the anterior displacement, the reactivated muscle activity dims the light bulb and returns it close to normal growth activity. In the boxed area, the upper open coil shows the potential of the anterior digastric muscle and other perimandibular connective tissues to reactivate and return the condyle back into the fossa once the advancement is released. The lower coil in the box represents the shortened inferior LPM. The open coil above the yellow condylar light bulb represents the effects of the stretched retrodiskal tissues.

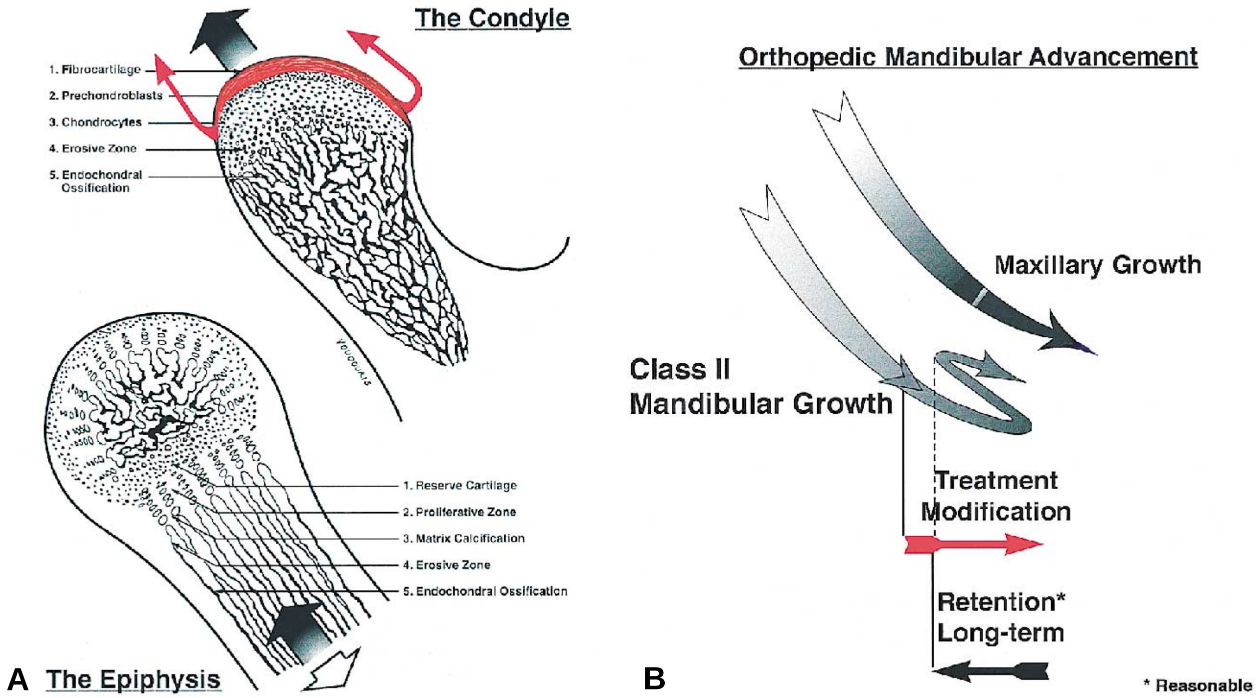


Fig 9. A, Significant anatomic differences between the condyle of the mandible and the epiphysis of long bones may permit greater modification of the condyle. The unique layer of fibrocartilage covering the condyle is absent in the epiphysis. In addition, compared with epiphyseal chondrocytes, condylar prechondroblasts are not surrounded by an intercellular matrix to isolate them from local factors. The chondrocytes are further oriented in a multidirectional fashion suitable for changes in growth direction in comparison to the columnar arrangement of the epiphyseal chondrocytes. **B**, Diagrammatic representation of an overall clinical concept of current condylar growth modification and retention. Orthopedic advancement has been associated with reduced muscle activity, while stimulating condylar proliferation (*red arrow*). However, after long-term retention when the appliances have been removed, the majority of condylar growth stimulation has been shown to be minimal in human beings (*black arrow*).

animal studies of glenoid fossa growth using condylar displacement,[78] condylectomies,[79-82] and condylar fractures[83,84] have verified this pronounced adaptive capability of the GF relative to the growing condyle.

Fibrocartilage is not easily visible macroscopically. The soft tissue connections to the condyle are deeply imbedded and difficult to assess. They overlap and intermingle in 3 dimensions seemingly without an obvious directional orientation similar to trabecular bone. This may account for the paucity of studies on viscoelastic physical interconnections and communications to the complex structure of the condylar head.

DISCUSSION

Epiphysis Versus Condyle

To offer an analogy following the literature review, the condyle appears to act like a light bulb on a dimmer switch. It lights up during advancement, dimming back down to near normal levels in retention. Its growth potential diminishes with age, whereas the glenoid fossa remodeling "lighting" potential lasts long into adulthood (Figs 2 and 8*B*).

Several investigations of relapse have lead to the conventional wisdom that C-GF growth modification cannot be maintained. This does not prove, however, that growth of the condyle is strongly predetermined by genetic factors, like an epiphyseal growth center. The condyle can restore its relational position within individual limits. Investigations should not exclude a possibility of identifying important triggers, stimuli, or hindrances for condylar growth, particularly as newer technologies for growth stimulation emerge.

The tissue-separating force[85] of the epiphyseal growth center, for example, is a main factor in determining the

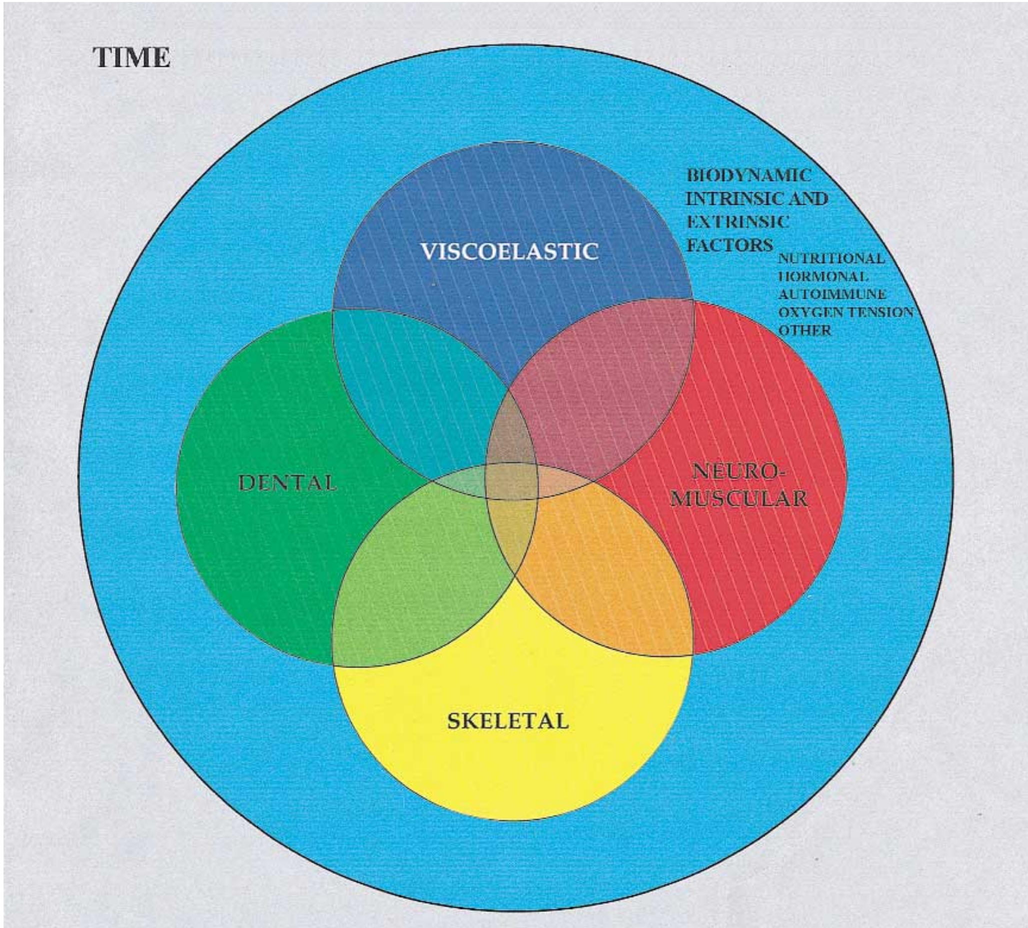


Fig 10. Biodynamic factors involved in condylar-glenoid fossa (C-GF) growth modification during orthopedic mandibular advancement in treatment and retention. Metabolic action describes the pump-like influx and expulsion of nutrients and other chemicals from the engorged blood vessels of the proliferating retrodiscal tissues (*dark blue region*) extending between the condyle and the fossa. This biodynamic action (*light blue circle*) occurs in the retrodiskal tissues and fibrocartilage during condylar displacement. The expulsion of these accumulated metabolites occurs during reseating of the protracted condyle and is clinically evident as relapse of the previously observed condition.

length of long bones. Primary epiphyseal cartilage has relatively little adaptive potential over the short-term and has no fibrocartilaginous cap. In contrast, the condyle does not have significant tissue-separating force and is dissimilar to the epiphysis functionally, anatomically (Fig 9*A*), immunologically,[86] chemically,[87-89] ontogenetically, or phylogenetically.[53] Condylar cartilage is capable of both a degree of healthy intrinsic growth and significant adaptive growth with short-term mechanical stimulation.[90] Although current results of long-term studies may appear to favor a genetic explanation of condylar growth**,** it must be recognized that the condyle simply does not look or act like an epiphysis during orthopedic treatment.[91-96]

RETENTION RELAPSE OF CONDYLAR MODIFICATION

The active return of the condyles to the fossae posttreatment appears to deactivate the modifications by compressing the condyle against the proliferated retrodiskal tissues. Any additional bone induction appears to be clinically insignificant at the condyle in the long-term (Fig 9*B*). The adaptive ability of the condyle is not clinically significant when the orthodontist cannot influence it positively through dentofacial orthopedic treatment over the long-term period. Condylar cartilage is considered a mechanical supporter that mends and extends itself in an attempt to regain function in the displaced condition when it is affected by environmental and functional factors including the function of the condyle within the GF.[97] Standard condylar growth studies may need to be considered in the future more in terms of long-term glenoid fossa modification.[98-102] The latter may be more closely related to the clinical corrections observed than may have been previously thought, especially for severe Class II type orthopedic changes with mandibular propulsive therapy.

CLINICAL IMPLICATIONS OF VISCOELASTICITY

Although orthopedic appliances do not appear to affect the growth of mandibles on a long-term basis, they are useful for dentoalveolar changes using condylar displacement and viscoelastic tissue forces. Anteroposterior and vertical changes also occur by differential eruption of the dentition. Clinically, transverse orthopedic changes are particularly useful. One key element in using propulsive orthopedic appliances is to avoid compression of the condyle against the eminence. This compression has been associated with reduced condylar growth, TMD, and osteoarthritic changes, including posttreatment degenerative condylar flattening in a number of isolated Herbst patients of preadolescent ages.[103-105]

In order to prevent condylar compression, it is suggested that a Herbst appliance be used with a thin posterior bite block and in combination with a rapid maxillary expander. The maxillary expansion reduces occlusal interferences and functional shifts by accommodating the wider portion of the anteriorly positioned lower arch. Herbst combinations with other appliances are not unusual, such as the headgear-Herbst, which has been used successfully for stable maxillary changes in human beings.[7] The Herbst-RME block has multiple advantages including a cushioning effect on the advanced condyle by moving it vertically away from the eminence. One purpose of the thin block is to relieve the articular disk from continuous compression[69] and reduce the possibility of condylar resorption in patients. Another use is buccal segment intrusion.

The purpose of progressive and continuous advancement of the mandible is to offset the proliferation of the activated retrodiskal tissues (Fig 7*A*) and to reactivate the metabolic pump-like action of the retrodiskal tissues. Some studies have suggested the maximum condylar prechondroblastic and chondroblastic response to be 6 weeks after initial activation[18,106,107] as a guide for planning subsequent reactivation. An adequately long retention period, perhaps until growth completion, is not practical for patients at this time, although it appears to be important. The retracting muscles of mastication (anterior digastric) as well as the other extended connective tissues surrounding the mandible have been associated with the pull of the condyle back into the fossa. This was clinically shown in children after surgical mandibular advancements[108] that caused deleterious effects on the final position of the mandible and condition of the condyle.

METHOD AND MATERIALS VARIANCES

Clinicians need to consider a number of important differences in the methods of C-GF modification studies. The proper selection of Class II control and treatment subjects and larger sample groups matched in current age and sex is essential. The type and duration of the appliance usage (eg, intermittent versus continuous appliance wear) do not appear to be a major factor determining the outcome of treatment.[109] On the other hand, differences between results during active treatment versus results of long-term retention should be most seriously considered. Duration of the active treatment varies between a few weeks and several years.[110] Similarly, the amount of advancement can vary significantly from 2 mm[111] to 9 mm.[112] The role of the maxillary growth and resulting changes in the occlusion[8,113] may be pertinent.

The type of analysis of results, for instance, with measurements such as the SNB angle or articulare (Ar) compared with condylion (Co) may also affect the interpretation of findings.[114,115] For instance, by using Ar-Pogonion immediately posttreatment, mandibular position (Fig 1*A*) may be affected by muscle dysfunction and by the proliferation of the retrodiskal tissues.[116-119] This does not constitute an overall increase in mandibular length compared with controls, and the condition is commonly referred to as dual, or "Sunday" bite, which is not considered to be a sign of successful orthopedic treatment.

OTHER USES OF ORTHOPEDICS

Although many orthodontists in North America use functional orthopedic appliances for mandibular displacement, a recent preliminary survey[120] showed that only a minority (21%) of the orthodontic respondents believe the mandible can be stimulated to grow beyond its intrinsic or genetic potential. According to them, the fact that all of the mandibular advancement appliances disocclude the two dental arches temporarily disables the inherent proprioceptive coupling of the maxillary and the mandibular dentition. This, in turn, allows the two jaws to grow or be otherwise displaced independent of each other. This theory, somewhat attractive because of its simplicity, probably cannot account for the full range of changes observed with the use of orthopedic functional appliances. It may, however, be an important adjunct to the other mechanisms described in this hypothesis, as well as in other hypotheses on the subject.[121]

It has been further suggested that no measurable long-term benefits for the mandible are derived from the first phase of "functional" appliance treatment in average two-phase treatment.[122] This indicates that C-GF modification may not need to be the prime target of orthopedic appliance therapy. Orthopedic appliances with imbedded expanders have been and are certainly useful today for interceptive treatment of selected early treatment patients with transverse skeletal maxillary constriction or environmentally constricted arch forms. Maxillary growth restriction, stable maxillary molar space regaining,[7,123] and initial retraction of severely tipped maxillary incisors with an imbedded Hawley retraction arch produce lip harmony, balance, and self-esteem. Finally, vertical dimension reduction (and A-P) changes through selective mandibular buccal segment eruption[124] for mandibular overclosure or buccal segment intrusion in skeletal open bites benefit from orthopedic appliances such as the Twin-block or Fränkel appliance for Class II correction. When orthodontic detailing is the primary objective, a single phase of interactive, self-engaging, edgewise appliance therapy is currently an ideal treatment choice, combining uniquely reduced resistance with full control in the system with a minimal number of appliances needed for unobstructed Class II molar correction. Relativistic thinking is critical for successful patient treatment.

Rather than one factor controlling C-GF modification, a balance of factors appears to be at work with orthopedic appliances. The presented hypothesis identifies at least 6 factors that interact and produce a positive change for each individual: skeletal (displacement), dental, neuromuscular, nonmuscular viscoelastic tissues including synovial fluids, biodynamic intrinsic and extrinsic factors, and maturational age contributing to adaptation in the TMJ complex (Fig 10).[125,126]

For over a century, muscle function has been implicated in bone formation[72,127-133] with relatively less attention given to the nonmuscular tissues with orthopedic treatment. This article explores a relativistic concept of growth using the 6 factors (including the gradual return of muscle activity) to describe the physical changes in the TMJ during orthopedic advancement appliance therapy more completely than theories presented thus far. Mechanisms of growth of the mandible are difficult to prove experimentally because they are multifactorial and complex. Craniofacial growth hypotheses are, therefore, rarely proposed because they are often subject to negative criticism. As a result, the number of hypotheses on the important causes of C-GF growth modification is minuscule in comparison to the vastly greater number of studies on the short-term clinical results of orthopedic appliances.

RELATIVISTIC THINKING FOR CAUSE AND DIAGNOSIS

The causes of condylar modification with orthopedic appliances are more important to address than short-term treatment results. Clinicians may be able to provide a greater consistency in Class II treatments by knowing what they can and cannot control. Significant mandibular growth modification and its retention on a long-term basis is debatable. The relative influence of each of the presented factors is significant in formulating orthodontic diagnoses and treatment-planning objectives. This is particularly relevant in considering the 3 vertical facial type characteristics, namely, high, low, and average FMA. Relativistic thinking is a key in orthodontic diagnoses, as our patients have dominant individual differences and respond differently to nearly identical treatment regimens.[26] Individual differences in growth rates and directions may explain some of the discrepancies reported in clinical studies in human beings. This may also be the reason that an intermittent displacement of the condyle induced increased condylar growth in some reports,[134-136] whereas in other investigations it was of minor clinical value.[111,137-139]

The muscles presumably win the interaction between the muscle and bone. However, factors other than muscles can and do affect bone. Some of these other interactions can be qualified by using relativistic reasoning. For instance, a dental factor as simple as a tooth in crossbite, or another nonmuscular factor such as chronic nasomucosal swelling, resulting in oral respiration and in subsequent severe maxillary constriction, can dominate the interaction between muscle and bone in malocclusion. Although early statements made by Wolff and Sicher[72,92] have exceeded their original usefulness, they have led to further thoughts, underscoring the need for a more specific yet broad relativistic outlook critical to clinicians in their treatment decisions.

FUTURE CONDYLAR BONE INDUCTION AND THE NEEDED MECHANISM

For orthodontists, identifying the primary trigger for adaptive growth of the advanced mandible and then achieving it with the use of orthopedic appliances is the key to successful treatment of certain malocclusions. The ideal objective would be to harness the full potential of this growth mechanism, exceeded only by controlling the cascade of secondary factors that cause the severe mandibular retrognathism and being able to intercept them.

Working in the clinic without a more specific understanding of the mechanisms of C-GF modification is akin to the use of a complex new appliance (hardware) without the prior reading of sequential operating instructions (software). The appliances that we need to understand have specific effects on the nonmuscular software. This is especially true if the objective is to alter the involved mechanisms some time in the future. Not knowing these mechanisms results in unexpected C-GF modifications that do not remain stable on a long-term basis.

The difference between the growth relativity hypothesis and the functional matrix theory is that the former is specific to the C-GF and identifies the soft tissues, fluids, and loci of force transduction that cause growth modifications when using orthopedic appliances. This is a macroscopic overview of a complex mosaic of numerous microscopic intrinsic and extrinsic[140] interactions.[141-143] They include electrophysiologic, neural sensory, oxygen tension, hormonal, nutritional,[144] and other factors. It identifies specifically where the soft tissue lines of communication affecting skeletal growth are located on, in, and around the condyle. The condylar growth modification mechanism should dictate the 3-dimensional construction of orthopedic appliances. A combined type of cast Herbst-RME block appliance has the potential to meet such a mandate. As the mechanisms of condylar growth modification and stability are better understood, they will provide clinically meaningful and stable C-GF modifications.

CONCLUSION

An hypothesis is presented for the mechanism of condylar-fossa growth modification with propulsive mandibular appliances, such as the Herbst and Twin-block that involves:

1. Displacement of the mandible
2. Viscoelastic tissue extension forces to the condyle through several different attachments
3. Transduction of forces radiating beneath the fibrocartilage of the glenoid fossa and condyle

The result is redirected and enhanced C-GF growth, primarily due to a significant remodeling. Since the glenoid fossa and the condyle are contiguous structures, the head of the modifying condyle is affected by the same 3 factors enumerated above. The condylar fibrocartilage may play the role of the conduit for force transduction. This was preliminarily confirmed by microscopic identification of insertions of the extended viscoelastic tissues directly into the pericondylar cap of fibrocartilage. There are several pieces of evidence to suggest that the condylar growth mechanism occurs relative to the glenoid fossa modifications and not necessarily as an independent and isolated phenomenon. The 2 structures are interconnected by retrodiskal tissues, engorged with nutrients from the enlarged blood supply during the condylar advancement. There is preliminary anatomic and histologic evidence to support the hypothesis that new bone formation at the displaced condyle is affected by nonmuscular viscoelastic forces directly and indirectly by transduction. Convincing arguments have been published that support condylar modifications during treatment. However, several studies have shown that they could not be maintained during reasonable long-term retention, for instance, longer than 2 to 3 years. In the future, orthopedic appliances may, with proper selection and skillful technique, successfully address condylar and glenoid fossa growth modification both in treatment and in retention.

FUTURE STUDIES

The growth relativity hypothesis is suitable for experimental verification. One suggestion is to test the effect of synovial fluid perfusion on C-GF growth modification by the continuous drainage of the synovial fluids in control and experimental subjects while using anterior mandibular displacement.

The growth relativity hypothesis is currently tested experimentally through the use of full occlusal coverage Herbst-Block and Twin-Block appliances for condylar displacement, stimulation of viscoelastic tissue, and transduction forces in primates. This method minimizes condylar compression typically found in a more traditional design of the Herbst appliance. It also affords the opportunity to use cephalometric, histomorphometric, and electromyographic methods to investigate the clinical significance of the observed changes (future publication).

It is important to note that young primates are described to have higher condylar growth rates than those of growing human beings. In addition, primates have orthognathic Class I occlusions, whereas some human beings require correction of mandibular retrognathism with Class II type malocclusions. However, with the close similarities between primate and human TMJs, direct examination and comparisons can be made of the primate soft tissue anatomy, including muscles. These observations in primates have positively impacted our understanding of how to treat, or to not treat, patients with severe retrognathism. The primate continues to be the premier model to study C-GF modifications, because of many biological similarities, including over 90% of human proteins and relatively minor species differences.[145-148]

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REFERENCES

1. Luce JV. Greek philosophy. System and science: Aristotle and the Lyceum, New York: Thames and Hudson; 1992. p. 110-30.
2. Herbst E. Dreissigjahrige Erfahrungen mit dem Retentions Scharnier. Zahnarztl Rundschau 1934;43:1515-24,1563-8,1611-6.
3. Clark WJ. The Twin-block technique: a functional orthopedic appliance system. Am J Orthod Dentofacial Orthop 1988;93:1-18, 1988.
4. Jasper JJ, McNamara JA Jr, Mollenhauer B. The modified Herbst appliance (Jasper Jumper). In: Graber TM, Rakosi T, Petrovic AG., editors, Dentofacial orthopedics with functional appliances, 2nd ed. St Louis: Mosby; 1997. p. 367-78.
5. Adams C, Meikle M, Norwick K. Dentofacial remodeling produced by intermaxillary forces in Macaca mulatta. Arch Oral Biol 1972;17:1519-35.
6. Wieslander L. Intensive treatment of severe Class II malocclusions with a headgear-Herbst appliance in the early mixed dentition. Am J Orthod 1984;86:1-13.
7. Wieslander L. Long-term effects of treatment with the headgear-Herbst appliance in the early mixed dentition: stability or relapse? Am J Orthod Dentofacial Orthop 1993;104:319-29.
8. Zarb GA, Carlsson GE. Temporomandibular joint function and dysfunction, 1st edition. St Louis: CV Mosby Co; 1979. p. 451.
9. Kreiborg S, Jensen BL, Moller E, Bjork A. Craniofacial growth in a case of congenital muscular dystrophy: a roentgenographic and electromyographic investigation. Am J Orthod 1978;74:207.
10. Tsolakis AI, Spyropoulos MN, Katsavrias E, Alexandridis K. Effects of altered mandibular function on mandibular growth after condylectomy. Eur J Orthod 1997;19:9-19.
11. Charlier JP, Petrovic A, Herman-Stutzmann JJ. The effect of mandibular hyperpropulsion on the prechondroblastic zone of the young rat condyle. Am J Orthod 1969; 55:71-4.
12. Petrovic AG, Stutzmann JJ, Gasson N. The final length of the mandible: is it genetically predetermined? In: Carlson DS, ed. Craniofacial biology. Monograph 10. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1981.
13. McNamara JA. Neuromuscular and skeletal adaptations to altered orofacial function. Monograph 1. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1973.
14. McNamara JA. Neuromuscular and skeletal adaptations to altered function in orofacial region. Am J Orthod 1973:64:578-606.
15. McNamara JA. The independent functions of the two heads of the lateral pterygoid muscle. Am J Anat 1973:138:197-206.
16. Baume L, Derischweiler H. Is the condylar growth center responsive to orthodontic therapy? an experimental study in Macaca mulatta. Oral Surg 1961;14:347-62.
17. Hiniker JJ, Ramfjord SP. Anterior displacement of the mandible in the adult rhesus monkey. J Prosth Dent 1966;16:503-12.
18. Stockli P, Willert H. Tissue reactions in the TMJ resulting from anterior displacement of the mandible in the monkey. Am J Orthod 1971;60:142-55.
19. McNamara JA, Carlson D. Quantitative analysis of temporomandibular joint adaptations to protrusive function. Am J Orthod 1979;76:593.
20. Nasibullin GG. Morphological changes in the temporomandibular joint on induced sagittal anomalies of occlusion in monkeys. Stomatologiia (Moskva) 1974;53:90-1.
21. Woodside DG, Voudouris JC, Altuna G, Metaxas A. Use of a facemask to protect the intra-oral area in cynomolgus monkeys. Lab Anim Sci 1983;33:600-2.
22. Massler M, Schour K. Postnatal growth pattern of the facial skeleton as measured by vital injections of alizarin red. J Dent Res 1944;23:218.
23. Brodie AG. Facial patterns: a theme on variation. Angle Orthod 1946;16:75-87.
24. Pancherz H, Littmann C. Morphologie und Lage des Unterkiefers bei der Herbst-Behandlung Eine kephalometrische Analyse der Veranderungen bis zum Wachstumabschlufl. Inf Orthod Kieferorthop 1989;21:493-513.
25. Pancherz H. The nature of Class II relapse after Herbst appliance treatment: a cephalometric long-term investigation. Am J Orthod Dentofacial Orthop 1991;100:220-33.
26. Pancherz H. Treatment of Class II malocclusions by jumping the bite with the Herbst appliance. Am J Orthod 1979;76:423-42.
27. McNamara JA, Bryan FA. Long-term mandibular adaptations to protrusive function: an experimental study in Macaca mulatta. Am J Orthod 1987;92:98-108.
28. Johnston LE Jr. Functional appliances: a mortgage on mandibular position. Austral Orthod J 1996;14:154-7.
29. Petrovic A. Control of postnatal growth of secondary cartilages of the mandible by mechanisms regulating occlusion. Cybernetic model. Trans Eur Orth Soc 1974;69-74.
30. Petrovic AG, Stutzmann JJ, Oudet CL. Control processes in the postnatal growth of the condylar cartilage in the mandible. In: Determinants of mandibular form and growth. McNamara JA Jr, editor. Monograph 5. Craniofacial growth series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1975.
31. Rees LA. Structure and function of the mandibular joint. Br Dent J 1954;96:125-33.
32. Whetten LL, Johnston LE Jr. The control of condylar growth: an experimental evaluation of the role of the lateral ptergoid muscle. Am J Orthod 1985;88:181-90.
33. Basmajian JV, Stecko G. A new bipolar electrode for electromyography. J Appl Physiol 1962;17:849.
34. Dubner R, Sessle BJ, Storey AT. The neural basis of oral and facial function. New York: Plenum, 1978.
35. Voudouris JC. Glenoid fossa and condylar remodeling following progressive mandibular protrusion in the juvenile Macaca fascicularis: a computerized, histomorphometric, cephalometric, and electromyographic investigation [Master of Science Thesis], Toronto, Ontario: Department of Orthodontics, University of Toronto, 1988.
36. Sessle BJ, Woodside DG, Bourque P, Gurza P, Powell S, Voudouris JC, Metaxas A, Altuna G. Effect of functional appliances on jaw muscle activity. Am J Orthod 1990;98:222-9.
37. Sessle BJ, Gurza SC. Jaw movement-related activity and reflexly induced changes in the lateral pterygoid muscle of the monkey Macaca fascicularis. Arch Oral Biol 1982;27:167-73.
38. Auf der Maur HJ. Electromyographic recordings of the lateral pterygoid muscle in activator treatment of Class II Division I malocclusion cases. Eur J Orthod 1980;2:161-71.
39. Pancherz H, Anehus-Pancherz M. Muscle activity in Class II Division I malocclusions treated by bite jumping with the Herbst appliance. Am J Orthod 1980;78:321-9.
40. Ingervall B, Bitsanis E. Function of masticatory muscles during the initial phase of activator treatment. Eur J Orthod 1986;8:172-84.
41. Petrovic A. Postnatal growth of bone: a perspective of current trends, new approaches, and innovations. In: Dixon AD, Sarnat BG, editors. Factors and mechanisms influencing bone growth. Prog Clin Biol Res 1982;101:297-331.
42. Petrovic A. An experimental and cybernetic approach to the mechanism of action of functional appliances on the mandibular growth. In: McNamara JA Jr, Ribbens KA, editors. Malocclusion and the periodontium. Monograph 15. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1984.
43. Petrovic AG, Stutzmann JJ. Research methodology and findings in applied craniofacial growth studies. In: Graber TM, Rakosi T, Petrovic AG, editors, Dentofacial orthopedics with functional appliances, 2nd ed. St Louis: Mosby 1997:36-7.
44. Moss ML. Functional analysis of human mandibular growth. J Prosth Dent 1960;10:1149.
45. Moss ML. The functional matrix. In: Kraus GS, Riedel RP, editors. Vistas in orthodontics. 1962;85-98.
46. Moss ML, Rankow R. The role of the functional matrix in mandibular growth. Angle Orthod 1968;38:95.
47. Moss ML, Salentijn L. The primary role of functional matrices in facial growth. Am J Orthod 1969;55:566.
48. Moss JP. An investigation of the muscle activity of patients with Class II Division 2 malocclusion and the changes during treatment. Trans Eur Orthod Soc 1975;87-101.
49. Gianelly AA, Moorrees CFA. Condylectomy in the rat. Arch Oral Biol 1965;10:101.
50. Durkin JF, Irving JT, Heeley JD. A comparison of the circulatory and calcification patterns in the mandibular condyle in the guinea pig with those found in tibial epiphyseal and articular cartilages. Arch Oral Biol 1969;14:1365.
51. Pimenidis MZ, Gianelly AA. The effect of early postnatal condylectomy on the growth of the mandible. Am J Orthod 1972;52:42.
52. Johnston LE Jr. The curious case of the chimerical condyle. In: Graber LW, editor. Orthodontics: state of the art, essence of the science. St Louis: CV Mosby. 1986. p. 88-99.
53. Enlow DH. Growth of the Mandible. In: Endow DE, Hans MG, editors. Essentials of facial growth. Philadelphia: WB Saunders, 1996. p. 57-78.
54. Posen AL. The influence of maximum perioral and tongue force on the incisor teeth. Angle Orthod 1972;42:285.
55. Posen AL. The application of quantitative perioral assessment to orthodontic case analysis and treatment planning. Angle Orthod 1976;46:118.

56. Linder-Aaronson S, Backstrom A. A comparison between mouth and nose breathers with respect to occlusion and facial dimensions. Odont Rev 1960;11:343.
57. Linder-Aaronson S. Effects of adenoidectomy on the dentition and facial skeleton over a period of 5 years. Trans Third Int Orthod Cong 1975;88-100.
58. Linder-Aaronson S. Respiratory function in relation to facial morphology and dentition. Br J Orthod 1979;6:1.
59. Altuna G, Woodside DG. Die Auswirkung von Ausbissblocken in Oberkiefer bei Macaca Rhesus (Vor Laufige Ergebnisse), Fortschr Kieferorthopadie 1977;38:391-402.
60. Altuna G. The effect of excess occlusal force on the eruption of the buccal segments and maxillary and mandibular growth direction in the Macaca monkey [Master of Science Thesis], Toronto, Ontario: Department of Orthodontics, University of Toronto, 1979.
61. Altuna G, Woodside DG. Response of the midface to treatment with increased vertical occlusal forces, treatment and post-treatment effects in monkeys. Angle Orthod 1985;55:251-63.
62. Graber LW. The alterability of mandibular growth. In McNamara JA Jr, editor. Determinants of mandibular form and growth. Monograph 4. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1975.
63. Joho JP. Changes in the form and size of the mandible in the orthopedically treated Macaca virus (an experimental study). Europ Orthod Soc Rep Congr 1968;161-73.
64. Storey AT. Physiology of a changing vertical dimension. J Pros Dent 1962;12:912-21.
65. Yamin CL. Effects of functional appliances on the temporomandibular joint and masticatory muscles in Macaca fascicularis [Master of Science Thesis]. Toronto, Ontario: Department of Orthodontics, University of Toronto, 1991.
66. Manns A, Miralles R, Guerrero F. The changes in electrical activity of the postural muscles of the mandible upon varying the vertical dimension. J Prosthet Dent 1981;45:438-45.
67. Rugh JD, Drago CJ. Vertical dimension: a study of clinical rest position and jaw muscle activity. J Prosthet Dent 1981;45:670-5.
68. Graber TM. The unique nature of the temporomandibular joint metabolism: the clinical implications. In: Bone formation and repair, Proceedings of the Int Symposium on Formation and Repair of Mineralized Extracellular Matrix, Hong Kong, Rabie ABM, Urist MR, editors, Amsterdam: Elsevier Publishing, 1997:143-53.
69. Nitzan DW. Intra-articular pressure in the functioning human temporomandibular joint and its alteration by uniform elevation of the occlusal plane. J Oral Maxillofac Surg 1994;52:671-9.
70. Levick JR. Joint pressure volume studies: their importance, design, and interpretation. J Rheumatol 1983;10:353.
71. Levick JR. Synovial fluid dynamics: the regulation of volume and pressure. In: Holborow EJ, Maroudas A, editors. Studies in joint diseases, vol 2. London: Pitman Medical; 1983. p. 153-240.
72. Wolff J. Virchow Arch Pathol Anat 1899;155:256.
73. Bjork A. Variation in the growth pattern of the human mandible: longitudinal radiographic study by the implant method, J Dent Res 1963;42:400-11.
74. Popovich F, Thompson GW. Craniofacial templates for orthodontic case analysis. Am J Orthod 1977;71:406.
75. Kantomaa T. The effect of posterior displacement of the glenoid fossa on mandibular growth: a methodological study in the rabbit. Eur J Ortho 1984;6:15-24.
76. Saunders SR, Popovich F, Thompson GW. A family study of craniofacial dimensions in the Burlington Growth Center sample. Am J Orthod 1980;78:394.
77. Marchac D, Renier D. Craniofacial surgery for craniosysnostosis, 1st edition. Boston: Little, Brown and Co; 1982; p. 35-8.
78. Angelopoulos G. Long-term stability of temporomandibular joint remodeling following continuous mandibular advancement in the juvenile Macaca fascicularis: a histomorphometric, cephalometric and electromyographic investigation [Master of Science Thesis], Toronto,Ontario: Department of Orthodontics, University of Toronto, 1991.
79. Sarnat BG, Engel MB. Effect of surgical removal of the condyle on the growing mandible: an experimental study of the Macaca rhesus monkey. Am J Orthod 1953;39:147.
80. Jolly M. Condyletomy in the rat: an investigation of the ensuing repair process in the region of the temporomandibular articulation. Austral Dent J 1961;65:243.
81. Sarnat BG. Postnatal growth of the upper face: some experimental considerations. Angle Orthod 1963;33:139.
82. Poswillo DE. The late effects of mandibular condylectomy. Oral Surg Oral Med Oral Path 1972;33:500-12.
83. Sprinz R. Healing in the fractures of the neck of the mandible in rats with detachment of the lateral pterygoid muscles. Arch Oral Biol 1970;15:1219-29.
84. Lindahl L, Hollender L. Condylar fractures of the mandible-II: a radiographic study of the remodeling process in the temporomandibular joint. Int J Oral Surg 1977;6:153-65.
85. Bernabei RL, Johnston LE Jr. The growth in situ of isolated mandibular segments. Am J Orthod 1978;73:24-35.
86. Bringham GP, Scaletta L, Johnston LE Jr, Occhino J. Antigenic differences among condylar, epiphyseal, and nasal septal cartilage. In: McNamara JA Jr, editor. The biology of occlusal development. Monograph 7. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1977.
87. Kuftinec MM, Miller SA. Alkaline and acid phosphatase activities during growth of long bones and mandible. Calcif Tissue Res 1972;9:1973-8.
88. Kuftinec MM, Miller SA. Bone growth in the neonatal rat. I. biochemical aspects of bone protein synthesis. Calcif Tissue Res 1973;11:105-11.
89. Kuftinec MM. Bone growth in the neonatal rat. II. Biochemical aspects of bone mineral incorporation. Calcif Tissue Res 1975;17:183-8.
90. Johnston LE Jr. A comparative analysis of Class II treatments. In: Vig PS, Ribbens KA, editors. Science and clinical judgement in orthodontics. Ann Arbor: Center for Human Growth and Development; 1986 p. 103-48.
91. Symons NBB. Studies on the growth and form of the mandible. Dent Rec 1951;71:5.
92. Sicher H. Growth of the mandible. Am J Orthod 1947;33:30-5.
93. Scott JH. The comparative anatomy of jaw growth and tooth eruption. Dent Rec 1951;71:149-67.
94. Baume LJ. Principles of cephalofacial development revealed by experimental biology. Am J Orthod 1961;47:881-901.
95. Baume LJ. Ontogenesis of the human temporomandibular joint. II. Development of the temporal components. J Dent Res 1970;49:864.
96. Koski D. Cranial growth centers: facts or fallacies? Am J Orthod 1968;54:566-83.
97. Spyropoulos MN, Tsolakis AI, Katsavrias E, Alexandridis K. Effects of experimental unilateral condylectomy followed by altered mandibular function on the maxilla and zygoma Eur J Orthod 1997;19:205-10.
98. Breitner C. Bone changes resulting from experimental orthodontic treatment. Am J Orthod 1940;26:521-47.
99. Dahan J, Dombrowsky KJ, Oehler K. Static and dynamic morphology of the temporomandibular joint before and after functional treatment with the activator. Trans Eur Orthod Soc. 1969;255-74.
100. Birkebaek L, Melsen B, Terp S. A laminagraphic study of the alterations in the temporomandibular joint following activator treatment. Eur J Orthod 1984;6:257-66.
101. Hinton RJ, McNamara JA. Temporal bone adaptations to protrusive function in juvenile and young adult monkeys (Macaca mulatta). Eur J Orthod 1984;6:155-74.
102. Woodside DG, Metaxas A, Altuna G. The influence of functional appliance therapy of glenoid fossa remodeling. Am J Orthod 1987;92:181-98.
103. Ruf S, Pancherz H. Long-term TMJ effects of Herbst treatment: a clinical and MRI study. Am J Orthod Dentofacial Orthop 1998;114:475-91.
104. Hagg U, Panchez H. Dentofacial orthopaedics in relation to chronological age, growth period and skeletal development: an analysis of 72 male patients with Class II Division 1 malocclusion treated with the Herbst appliance. Eur J Orthod 1988;10:169-76.
105. Pancherz H, Haag U. Dentofacial orthopaedics in relation to somatic maturation: an analysis of 70 consecutive cases treated with the Herbst appliance. Am J Orthod 1985;88:273-87.
106. McNamara JA, Connelly TA, McBride MC. Histologic studies of temporomandibular joint adaptations. In: McNamara JA Jr, editor. Determinants in mandibular form and growth, Monograph 4. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1975.
107. Elgoyhen JC, Moyers RE, McNamara JA, Riolo ML. Craniofunctional adaptation to protrusive function in young rhesus monkeys. Am J Orthod 1972;62:469-80.
108. Huang CS, Ross RB. Surgical advancement of the retrognathic mandible in growing children. Am J Orthod 1982;82:89-103.
109. Sahm G, Bartsch A, Witt E. Micro-electronic monitoring of functional appliance wear. Eur J Orthod 1990;12:297-301.
110. Baume LJ, Haupl K, Stellmach R. Growth and transformation of the temporomandibular joint in an orthopedically treated case of Pierre Robins syndrome. Am J Orthod 1959;45:901-16.
111. Jacobsson SO. Cephalometric evaluation of treatment effect on Class II Division 1 malocclusion. Am J Orthod 1967;53:446-57.
112. Woodside DG, Reed RT, Doucet JD, Thompson GW. Some effects of activator treatment on the growth rate of the mandible and position of the midface. In: Cook JT, editor. Trans of Third International Orthodontic Congress. St Louis: CV Mosby Co; 1975.
113. Pancherz H, Fackel U. The skeletofacial growth pattern pre- and postdentofacial orthopedics: a long-term study of Class II malocclusions treated with the Herbst appliance. Eur J Orthod 1990;12:209-18.
114. Trayfoot J, Richardson A. Angle Class II Division 1 malocclusions treated by the Andresen method. Br Dent J 1968;124:516-9.
115. Fischer-Brandies H. Cephalometric changes in angle Class II treatment. Int J Orthod 1989;27:9-13.
116. DeVincenzo JP, Huffer RA, Winn MW. A study in human subjects using a new device designed to mimic the protrusive functional appliances used previously in monkeys. Am J Orthod 1987;9l:213-24.
117. DeVincenzo JP. Changes in mandibular length before, during, and after successful orthopedic correction of Class II malocclusions, using a functional appliance. Am J Orthod Dentofacial Orthop 1991;99:241-57.
118. Stickel A, Pancherz H. Can “articulare” be used in the cephalometric analysis of mandibular length? A methodologic study. Eur J Orthod 1988;10:362-8.
119. Valant JR, Sinclair PM. Treatment effects of the Herbst appliance. Am J Orthod 1989;95:138-47.
120. Hamilton D. Keynote address, Edward H. Angle Society, October 1995.
121. Johnston LE Jr. Growing jaws for fun and profit: a modest proposal. In: McNamara JA Jr, editor. Growth modification: what works, what doesn’t, and why. Monograph 35. Craniofacial Growth Series. Ann Arbor: Center for Human Growth and Development, University of Michigan, 1999.

122. Livieratos FA, Johnston LE Jr. A comparison of one-stage nonextraction in matched Class II samples. Am J Orthod Dentofacial Orthop 1995;108:118-31.
123. Pancherz H, Hansen K. Occlusal changes during and after Herbst treatment: a cephalometric investigation. Eur J Orthod 1986;8:215-28.
124. Righellis EG. Treatment effects of Frankel, Activator and extraoral traction appliances. Angle Orthod 1983;53:107-21.
125. Behrents RG. Growth in the aging craniofacial skeleton. Monograph 17. Craniofacial Growth Series. Ann Arbor: University of Michigan, 1985.
126. Moaddab MB, Dumas AL, McDonough J. Anthropological study of the development of the temporomandibular joint. IADR/AADR Abstract 1985;269.
127. Robin P. Demonstration practique sur la construction et la mise en bouch díun nouvel appareil de redressement. Rev Stmatol 1902:9:561-90.
128. Washburn SL. The relation of the temporal muscle to the form of the skull. Anat Rec 1947;99:239-48.
129. Harvold EP. The role of function in the etiology and treatment of malocclusion. Am J Orthod 1968;54:883-98.
130. Harvold EP, Vargervik K. Morphogenetic response to activator treatment. Am J Orthod 1971;60:478-90.
131. Vargervik K, Harvold EP. Response to activator treatment in Class II malocclusions. Am J Orthod 1985;88:242-51.
132. Ingervall B, Thilander B. Relation between facial morphology and activity of the masticatory muscles. J Oral Rehabil 1974;1:131-47.
133. Linder-Aronson S. Adenoids: their effect on mode of breathing and nasal airflow and their relationship to characteristics of the facial skeleton and the dentition. Acta Otolar suppl 1970;265.
134. Marcher JF, Harris JE. Mandibular growth and Class II treatment. Angle Orthod 1966;36:89-93.
135. Falck F, Frankel R. Clinical relevance of step-by-step mandibular advancement in the treatment of mandibular retrusion using the Frankel appliance. Am J Orthod 1989;96:333-41.
136. Kerr WJ, TenHave TR, McNamara JA Jr. A comparison of skeletal and dental changes produced by function regulators (Fr-2 and Fr-3). Eur J Orthod 1989;11:235-42.
137. Hamilton SD, Sinclair PM, Hamilton RH. A cephalometric, tomographic, and dental cast evaluation of Frankel therapy. Am J Orthod 1987;92:427-36.
138. Pancherz H. A cephalometric analysis of skeletal and dental changes contributing to Class II correction in activator treatment. Am J Orthod 1984;85:125-34.
139. Harvold EP. Altering craniofacial growth: force application and neuromuscular-bone interaction. In: McNamara JA Jr, editor. Proceedings of Moyers Symposium. Ann Arbor: University of Michigan Press, 1982.
140. Stutzmann JJ, Petrovic AG. Intrinsic regulation of the condylar cartilage growth rate. Eur J Orthod 1979;1:41.
141. Moss ML. The functional matrix hypothesis revisited. 1: the role of mechanotransduction. Am J Orthod Dentofacial Orthop 1997;112:8-11.
142. Moss ML. The functional matrix hypothesis revisited. 2: the role of an osseous connected cellular network. Am J Orthod Dentofacial Orthop 1997;112:221-6.
143. Moss ML. The functional matrix hypothesis revisited. 3: the genomic thesis. Am J Orthod Dentofacial Orthop 1997;112:338-42.
144. Kutinec MM, DePaola DP: Nutrition in the growth and development of oral tissue. Symposium on Nutrition. Dent Clin N Am 1976;20:441-56.
145. Endow DH. The human face. New York: Harper and Row Publishers; 1968.
146. Angel JL. Factors in temporomandibular joint form. Am J Anat 1948;83:233.
147. Schumacher GH. Functionelle Morphologie der Daumuskulatur, Gustav Fischer Verlag, Jena, 1961.
148. Zimmerman HI. The normal growth and remodeling of the temporomandibular joint of Macaca mulatta [Master of Science Thesis]. Seattle: Department of Orthodontics, University of Washington; 1971.