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Skeletal and dental considerations in orthodontic treatment mechanics: a contemporary view[§]

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SUMMARY Orthodontics has undergone a paradigm shift in the last 40 years. There have been both technical and philosophical changes ushered by the development of new appliances, techniques, and by the explosion in the amount of research being conducted all around the world. However, the application of any new concept requires a firm understanding of the fundamentals of orthodontics. This paper presents a broad review of some fundamental concepts of treatment mechanics that enable us to bring about skeletal and dental correction of the presenting malocclusion. The basic concepts of facemask therapy, mechanics, and biology of tooth movement will be discussed with an insight into the challenges facing us in the future.

Introduction

Orthodontics is a dynamic and rapidly evolving science. In the past couple of decades, sweeping changes and paradigm shifts in diagnosis, imaging, treatment mechanics, and biological principles of tooth movement have ushered a new era. However, the essentials of orthodontics still remain the same. Through this paper, we intend to elucidate some basic concepts of treatment mechanics to achieve predictable changes in the skeletal, dental, and soft tissue structures of the face.

Orthodontics and dentofacial orthopaedics encompasses modification/alteration of the teeth and the supporting bones to attain desirable changes in their relative position so that aesthetics, function, and oral health of the patient can be improved. A complete understanding of the aesthetic development of the face, the mechanics involved in growth modification, and the tooth movement is important. Also, an appreciation of the biological mechanisms is critical.

Class III orthopaedic treatment

Facemask therapy

The current practise of orthodontics frequently uses extraoral forces to treat malocclusions and skeletofacial disharmonies. These extraoral devices generate therapeutic forces at the teeth, which are transmitted to the periodontal ligament, bone, and ultimately to its articulations. It is believed that these forces correct skeletal disharmonies either by inhibiting or by redirecting the growth of jaws or by inducing biologic alterations at facial sutures and cartilaginous areas.

The orthopaedic changes seen in experimental studies on primates have been dramatic (Janzen and Bluher, 1965; Nanda, 1978a,b), but the changes reported in clinical studies have been of small magnitude (Nanda, 1980; Ritucci and Nanda, 1986). This brings up the obvious question 'Why is there such a glaring difference in the outcomes?'.

Skeletal class III malocclusion in growing children remains one of the most challenging problems in orthodontics. It has been suggested that the majority of subjects with a skeletal class III malocclusion present with maxillary retrusion and a normal and/or prognathic mandible (Ellis and McNamara, 1984; Guyer *et al.,* 1986; Enacar *et al.,* 2003).

Clinical studies have shown that 2–5 mm of underjet correction can be obtained with 8–12 months of maxillary protraction (Hata *et al.,* 1987; Hickham, 1991; Baik, 1995). This is the result of a combination of forward movement of the maxilla, downward and backward rotation of the mandible, labial tipping of the maxillary incisors, and lingual tipping of the mandibular incisors. A meta-analysis on the effectiveness of protraction facemask treatment found that the average change in the Wits appraisal was 4–6 mm, and the average horizontal A point movement was 1–3 mm (Kim *et al.,* 1999). This clearly shows the pronounced 'dental' effects of such a therapy, which might not be always desirable.

Differences in treatment outcomes or pronounced dental effects rather than skeletal might also arise due to poor understanding of the mechanics involved. Orthopaedic force on the nasomaxillary complex is directed along the occlusal plane, rather than through the centre of resistance of the maxilla, which is approximately located between the
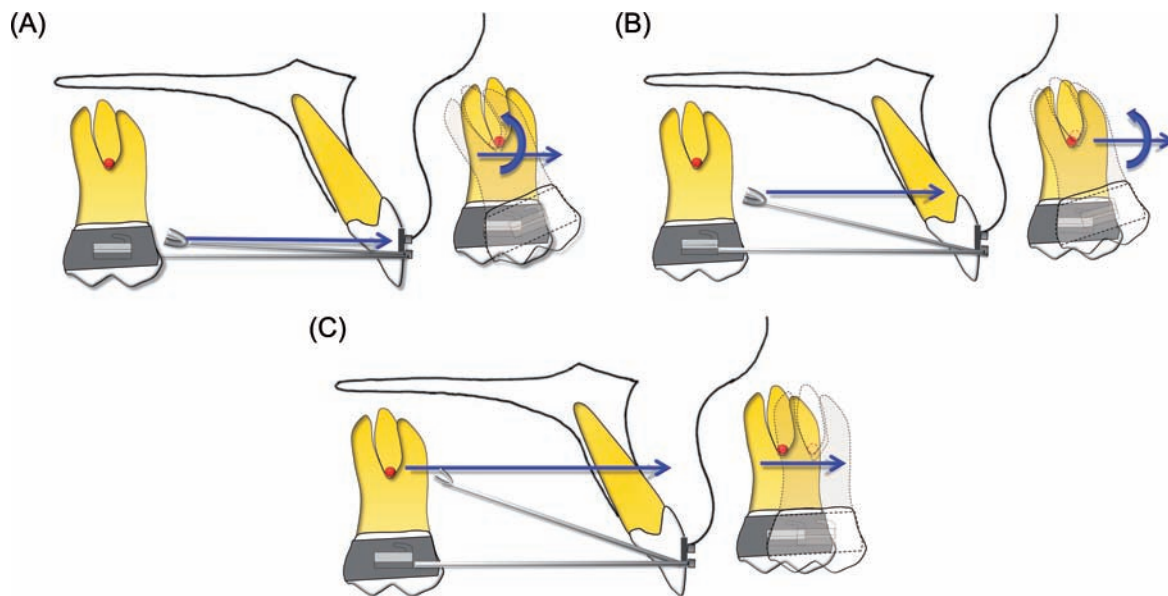
Figure 1 Diagrammatic representation of the different types of responses, which can be obtained by using the protraction headgear showing the versatility of the appliance. The maxilla and/or maxillary dentition as a whole is represented only by a maxillary molar. (A) A force at a level as shown by the dotted arrow will create a large moment on the molar as well as its mesial displacement. A force of this nature is seldom required in patients in skeletal class III. (B) By changing the position of the outer bow, a controlled tipping of the molar can be obtained. (C) A force delivered through the centre of resistance of the molar will deliver a desirable translatory mesial movement of the molar. Since the centre of resistance of the maxillary dentition is difficult to locate, the outer bow can be kept at the level of premolars. As the treatment progresses, the outer bow can be adjusted accordingly.

mesiobuccal cusp of the maxillary molar and infraorbitale (Figure 1). As a result, bone remodelling occurs not only at the circum-maxillary sutures but also within the periodontal ligament. Another side effect of protracting along the occlusal plane is the loss of arch length due to mesial movement of the posterior teeth, especially in the mixed dentition or in patients with several congenitally missing teeth (Keles *et al.,* 2002).

There has been a lot of variation in the clinical results obtained with the application of reverse pull headgear. Although patient compliance and timing of treatment are critical factors for successful therapy, the biomechanical considerations in the application of reverse pull headgear also play a key role. In order to understand the mechanical principles involved, there are four important factors to be considered. They are as follows: 1. centres of rotation (Crot) of the maxilla/the nasomaxillary complex or the teeth created by the force applied, 2. direction of force, 3. magnitude of the force, and 4. duration of force application (Nanda and Goldin, 1980).

The degree of rotation or translation of the maxillary complex is a function of the line of force in relation to the centre of resistance of the maxilla. The rotational changes can be quantified by determining the 'moment of force'. By simply changing the moment of the force and the direction of the force with respect to the Cres, the centre of rotation can easily be altered. For example, a protraction force to the maxilla below the Cres produces a counter-clockwise rotation of the maxilla, which may not be favourable for patients with minimal overbite or open bite tendency (Figure 1).

The direction of force application can easily be altered in a patient as shown in Figure 2.

The magnitude of force required to protract midfacial bones is primarily influenced by the age of the patient. Studies have shown that sutures become more complex with skeletal maturation (Melsen, 1975). It can be surmised that a 6–7-year-old patient may not need the same force as a 12–13 year old might need. Based on the age of a patient, the amount of force may vary from 300 to 800 grams on each side. The duration of force is also a critical factor. Based on previous research (Stevenson *et al.,* 1990; Igarashi *et al.,* 1998), force duration of 12 hours/day, every day for at
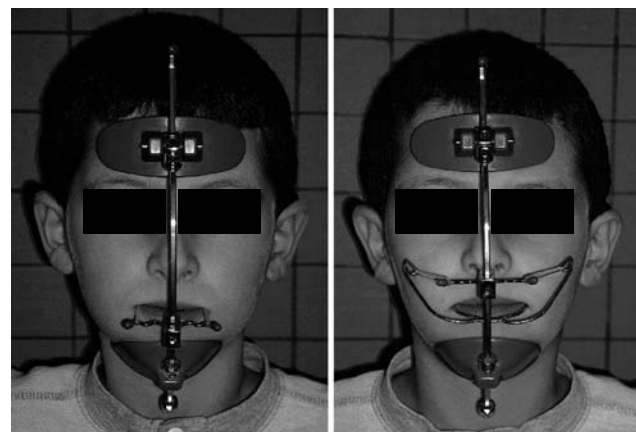
Figure 2 A patient showing two different points of force application for facemask therapy. (A) At the occlusal plane. (B) Above the occlusal plane.

least 12–18 months depending upon the rapidity of growth and patient co-operation, is recommended. However, it is important to remember that the overall treatment changes produced will be a combination of both orthopaedic and dental effects. In order to avoid side effects and have greater orthopaedic effects, some researchers (Baccetti *et al.,* 1998; Kircelli and Pektas, 2008; Isci *et al.,* 2010) have recently suggested combining rapid maxillary expansion (RME) with facemask therapy in order to 'loosen up' the articulation of the circumaxillary sutures. This might help in gaining greater skeletal effects.

Implants for class III treatment

In the past few years, newer treatment methods with skeletal anchorage in the maxillary buttress have been developed to minimize dentoalveolar compensations (Singer *et al.,* 2000; Enakar *et al.,* 2008). Bone-anchored maxillary protraction treatment has been shown to produce significant orthopaedic changes compared with untreated class III subjects. Up to 3 mm of maxillary protraction has been reported as compared with conventional or RME-assisted facemask therapy (Cevidanes *et al.,* 2010; Nyugen *et al.,* 2011). Also, there are minimal side effects like flaring of maxillary incisors and clockwise rotation of the occlusal plane. Additionally, the protraction force can be adjusted according to the centre of resistance of the nasomaxillary complex by careful implant/plate placement; thereby, achieving good control on the entire arch. However, this technique is still in its infancy. More evidence is needed through long-term studies involving retention based on quantitative measures obtained by three-dimensional imaging to fully realize the true potential of implant-based facemask therapy.

Chin cup treatment

The use of the chin cup to treat class III skeletal deformities is not a new concept to the orthodontic profession. Over the years, there has been considerable debate over the actual effects of chin cup therapy. Numerous studies have analysed the effect of chin cup therapy on the mandible and on the nasomaxillary complex including the cranium (Wendell *et al.,* 1985; Ritucci and Nanda, 1986). Our longitudinal studies of patients up to the age of 13 years, treated at Tohoku Dental School in Sendai, Japan have shown that the downward vertical growth of the midface was inhibited by use of the chin cup. Posterior vertical development was restricted more than anterior vertical development, resulting in a clockwise rotation of the maxilla and midface. The mandible exhibited less downward displacement relative to cranial base during treatment. However, a follow up of same patients to adulthood have shown that the effects of chin cup treatment were not consistently maintained (Sugawara *et al.,* 1990; Sugawara and Mitani, 1997). No differences could be found in mandibular dimensions between treated and untreated subjects.

Therefore, in the present scenario, patients having a true class III with a prognathic mandible rarely benefit from chin cup therapy, especially in the long term; only those who have a short facial height respond favourably. Similar to what we see with facemask therapy.

Mechanics of tooth movement

The fundamentals of tooth movement lie in understanding two broad concepts: the biology and the mechanics involved so that a predictable and calibrated movement can be attained with minimal side effects. In this section, we will focus on the fundamentals of mechanics as the orthodontist is in complete control of this particular aspect of tooth movement. Once the objectives of a treatment plan are in place, the challenge is to execute them as accurately as possible. As with any other branch of science, mechanics in orthodontics is also governed by a specific set of laws that offer themselves to be measured and calibrated so that it becomes repeatable and reproducible any number of times.

Orthodontic tooth movement also follows certain principles of classical or Newtonian mechanics that need to be understood to carry out a particular type of tooth movement. It is important to remember that brackets by themselves do not move teeth. They have to work in conjunction with a set of wires to generate the required forces and moments for moving teeth. Placing bends in a wire at strategic locations between two or more brackets is one way of using these laws to move teeth in a predictable fashion. This is often done during the finishing stages of treatment. The other is to offset the brackets in relation to each other to create the same forces and moments.

Bends placed on a wire between two attachments can essentially create two kinds of force systems depending upon how the wire is engaged in the two attachments. They are as follows:

1. One-couple force system
2. Two-couple force system.

One-couple force system

These force systems are established between two attachments when a couple is created at one end of an attachment and a single force at the other. This usually involves a wire with a bend and inserted into a bracket/tube, whereas at the other end, instead of placing it in a bracket/tube slot, it is just tied to the attachment so that only one point of contact is created. Due to the simple configuration of the action and reaction forces this system generates, it is called a statically determinate force system, i.e. all the forces and moments created by such a system can be readily discerned, measured, and evaluated with remarkable precision. There
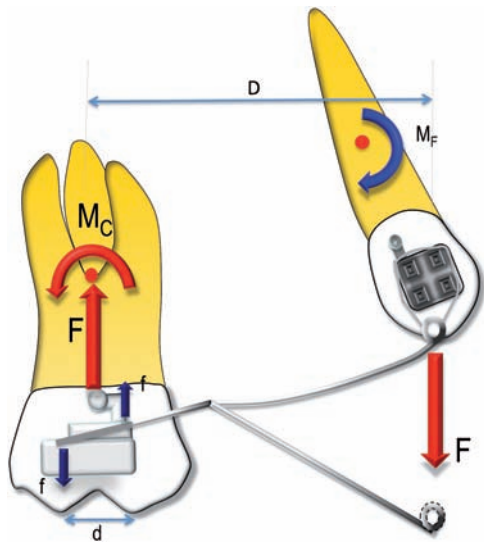
Figure 3 A cantilever spring design for extrusion of a canine (a one-couple force system). The dotted line indicates the passive state of the spring, while the solid design shows it is in the activated state or in other words from this point onwards the spring will gradually undergo deactivation. The force (F) exerted on the canine and molar as per Newton's third law is equal and opposite. The spring due to the activation generates a couple in the auxillary tube (Mc), where Mc = FXD (D is the distance between the Cres of the molar and the point of application of the force on the canine). Mc can also be calculated by the product of the force of the couple 'f' and the length of the auxillary tube (d), i.e. Mc = fxd. Because the force does not pass through the Cres of the canine, it generates a moment (Mf).

are a number of situations where we make use of such a force system:

1. A cantilever spring design (Figure 3) is the essential component of all appliances utilizing the one-couple force system. The most common application of such a design is utilized in 'extrusion of an impacted canine'. It can also be used for uprighting of tipped teeth, intrusion, and retraction of anterior teeth etc. Figure 3 illustrates the mechanics involved when utilising a cantilever spring for canine extrusion. The mechanics shown applies to all one-couple force systems. Note how the spring is simply tied to the canine bracket and not inserted in the bracket slot so that there is only a single point of force application as opposed to the two-point contact in the molar auxillary tube.

2. An intrusion arch (Figures 4 and 5) works on the same principle as illustrated previously. It can be made out of 0.016×0.022-inch or 0.017×0.025-inch Connecticut beta titanium archwires. Alternatively preformed intrusion archwires, the Connecticut Intrusion arch (Ultimate Wireforms, Bristol, Connecticut), fabricated from a nickel titanium alloy, which provides the advantage of shape memory, spring back, and light continuous force distribution can also be used (Nanda *et al.,* 1998). The appliance set up includes two passive posterior (stabilizing) units (usually the molars and premolars, bilaterally) and one active anterior unit (the intrusion arch). All the
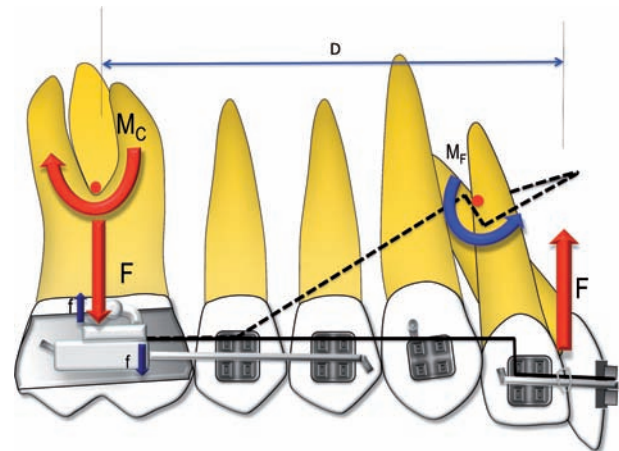
Figure 4 Mechanics of an intrusion arch to correct a deep bite. The forces and moments described are exactly similar to the one described in Figure 3.

units are stabilized with stiff or rigid segmented wires (0.019×0.025-inch stainless steel or higher dimension wires). Inclusion of as many teeth as possible in the posterior segment helps to minimize the side effects. The anterior segment that includes either two or four incisors is constructed with similar wires.

The intrusion arch is activated by placing a 30° gingival bend 2–3 mm mesial to the molar tubes so that the wire lies passively in the vestibular sulcus. Activation is done by bringing it occlusal and tying it to the anterior segment so that a point contact is established as opposed to placing it directly into the bracket slots as is done with the utility arch (Ricketts, 1976a,b). The intrusion arch can also be tied back or cinched to prevent flaring of the incisors if the intrusive force is being applied anterior to the centre of resistance (Cres) of the incisors. The reciprocal action of the intrusion arch on the molars or the buccal segments is the extrusion and/or distal tip back of the crowns. Recent evidence has shown that the intrusive force can be made so light so that those reactive forces on the anchor teeth remain well below the force levels needed for extrusion and tipping (Steenbergen *et al.,* 2005). Therefore, the use of a headgear to prevent side effects can be avoided. Additionally, low forces also help in minimising root resorption. On an average, after the initial activation period of 3–4 weeks, the intrusion arch should intrude 0.4–0.6 mm per month.

Two-couple force system

These force systems are established between two attachments when a wire is inserted in the bracket slots of two brackets/tubes. As the name suggests, these force systems involve forces and couples at both the attachments when a straight wire is placed in a pair of non-aligned brackets or when a bend is placed between two aligned brackets. Understanding the dynamics of this two-bracket unit is fundamental

Figure 5   Intrusion arch-aided deep bite correction.

in understanding the mechanical principles guiding the movement of teeth with sliding mechanics.

When compared with the force system described in the previous section (i.e one-couple force systems), this constitutes a statically indeterminate force system, i.e. it gets too complex to 'precisely' determine all the forces and moments involved at both the attachment at a particular time. In this system, when the wire is placed over the slots of the two brackets where it will be inserted, the angle of entry of the wire at each bracket slot does show which bracket has the larger angle of entry and, therefore, the larger moment. This is important because, irrespective of the direction of the moment at the second bracket, the larger moment will dictate the direction of the associated net equilibrium of forces acting at each bracket. For ease of understanding about the nature of forces and moments created at both the ends, the two-couple force systems can be classified into certain types of 'geometries' (Figure 6):

1. Step bends
2. Centred 'V' bends
3. Off-centred 'V' bends.

Each of these bends is distinct from the other in terms of the forces and moments produced at both the ends (Burstone and Koenig, 1988). It is important to remember that using a straight wire but offsetting the bracket positions relative to each other can also create the same forces and moments

for all the above geometries (Burstone and Koenig, 1974). These mechanics are critical in understanding the tooth movement brought about by an active transpalatal arch, utility arch, or any other kind of 2 × 4 appliance.

All systems reported in the past and all systems that will be reported in the future will use these principles. The orthodontists who understand and identify them will have better control of their treatment mechanics and greater efficiency in tooth movement. Once we are able to unravel the basic mechanics of tooth movement in order to make tooth movement more efficient with minimal side effects, it is important to start integrating the newer advances happening in orthodontics to these basics and move forward.

**Mechanics of skeletal anchorage**

Conventional mechanics can easily carry out dental movements requiring mild-to-moderate anchorage; however, those requiring high anchorage need precise control of tooth movement for successful correction. Mini-implants (MIs) have revolutionized clinical orthodontics by changing the way we manage anchorage (Park *et al.,* 2005, Upadhyay *et al.,* 2008a,b). They have become indispensable for the treatment of many clinical cases and have developed into valuable orthodontic adjuncts for expanding the scope of biomechanical therapy and enhancing the clinical outcomes (Uribe and Nanda, 2009).
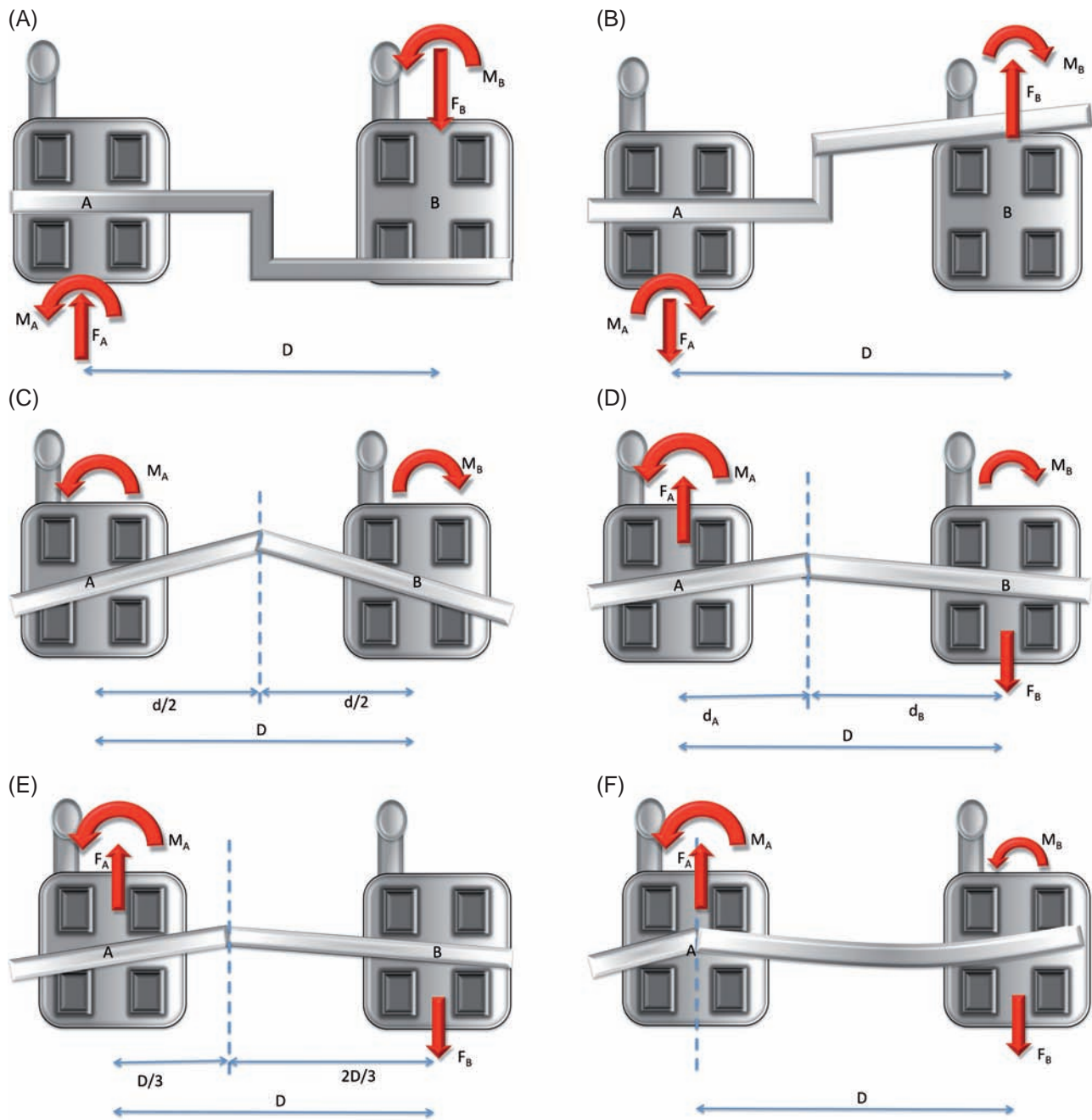
Figure 6 A two-couple force system between two brackets. M_A = Moment generated at bracket A, M_B = Moment generated at bracket B, F_A = Force generated at bracket A, F_B = Force generated at bracket B, D is the distance between the two brackets, d_A = Distance between bracket A and the bend in the wire, d_B = Distance between bracket B and the bend placed in the wire. (A) and (B) step bends. (C) A bend placed exactly in between the two brackets. (D) A bend placed in such a way that 1/2 D <d_A> 2/3 D. (E) A bend placed at 1/3 D. (F) A bend placed at bracket A.

MIs help in eliminating the element of unpredictability that is generally associated with other traditional anchorage units thereby making the orthodontists completely in charge of the tooth movement desired. However, understanding the mechanics involved here is of paramount importance as it might differ from what we are traditionally accustomed to. Here is a simple example to elucidate the need for understanding the mechanics with MIs. When using conventional

mechanics, force application is usually parallel to the occlusal plane, and hence, we are required to deal with the force only in one plane. However, because MIs are usually placed apical to the occlusal plane into the bone between the roots of teeth, force applied is always at an angle (Figure 7A and 7B). Therefore, besides the retractive force (r), there is also an intrusive force (i). In addition, with conventional mechanics, the molars or posterior segments usually serve
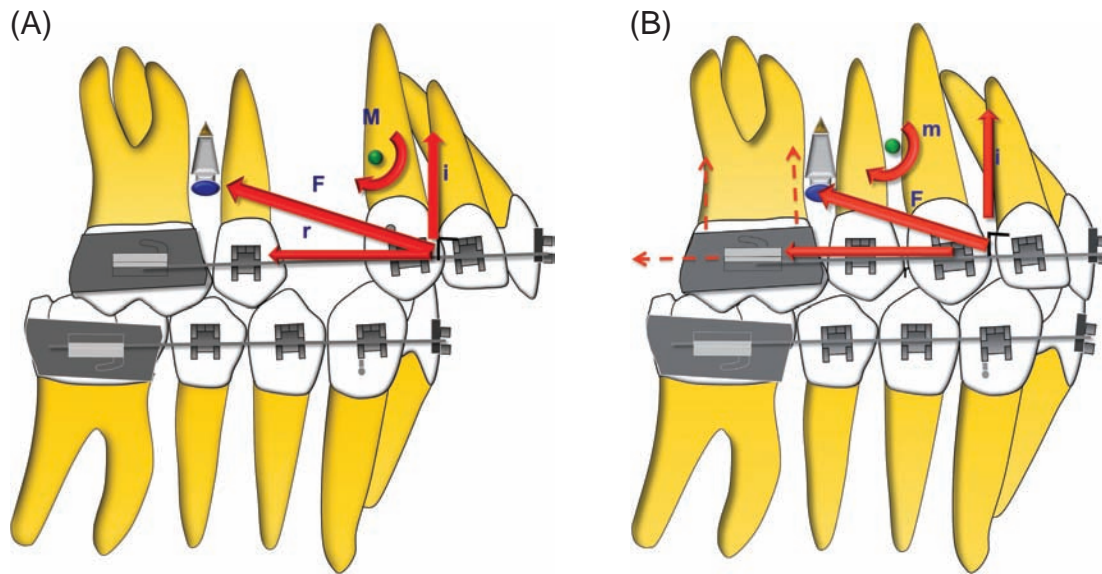
Figure 7 Biomechanical design of the force system involved: (A) during en-masse retraction of the anterior teeth with mini-implant anchorage. Here, F >> r > i. (B) After space closure. Note the increase in the angulation of the total force relative to the occlusal plane. Here, F >> r ≈ i) (F, total force; I, intrusive component; r, retractive component; M, moment on the anterior segment; m, moment on the entire arch).

as anchor units, with the rest of the arch as the active unit. The force system here has to be differentially expressed between the active and the anchorage unit within the same arch. In contrast, when MIs are incorporated as the third counterpart, selective movement of the anterior and posterior segments is possible. Let us try to establish the mechanics involved during en-masse retraction of anterior teeth by applying some mechanical principles supported by recent clinical studies (Upadhyay *et al.,* 2008a,b, 2009).

Space closure with MIs

While retracting anterior teeth in a full-cusp class II malocclusion or in a bialveolar dental protrusion case, anchorage control assumes profound importance because maintaining the posterior segment relation becomes very critical. A loss in molar anchorage can not only compromise correction of the anteroposterior discrepancy but can also affect the overall vertical dimension of the face. The application of MI-supported anchorage can circumvent the anchorage issues in such situations. The preferred location for MI placement is between the roots of the second premolars and first molars close to the mucogingival junction. A 0.017 × 0.025-inch stainless steel archwire and a force of 150–200 g are considered as optimum conditions for efficient retraction of the maxillary anterior teeth (Upadhyay *et al.,* 2008a,b, 2009).

According to Figure 7A (a pictorial description of the initial force system for en-masse retraction), the force (F) exerted by the nickel–titanium coil springs (bilaterally) has two distinct components: a larger and predominantly retractive force (r) and a smaller intrusive force

(i), causing en-masse retraction and some intrusion of the anterior teeth (Upadhyay *et al.,* 2010). Additionally, there is a clockwise moment (M) on the anterior segment as the total force passes below the estimated centre of resistance of the anterior teeth. This moment causes the anterior teeth to tip, in spite of the stiffness of the rectangular archwire, because a 0.017×0.025-inch stainless steel archwire has approximately 12° of play in a 0.022-inch slot assuming that the wire is completely passive when retraction starts (Schwaninger, 1978). If the anterior teeth are flared at the beginning, more tipping will be observed, as the effective play will be on the higher side. Once the anterior teeth have tipped by the amount of play available between the bracket slot and the wire, no further tipping occurs as the brackets lock onto the wire in that position. A transalatory movement of the anterior teeth can be expected if the retractive force is continued; however, biological limitations can also play a decisive role. Once the extraction spaces are closed, contact between the canine and the second premolar is established. From this point on, further continuation of the nickel–titanium coil springs results in transmission of the total force to the posterior segments through the interdental contacts, producing a distal and intrusive force on the posterior teeth and a moment (M) on the entire arch (Figure 7B).

Enhancing treatment efficiency

Treatment efficiency is defined as better result in a shorter period of time. All the concepts discussed thus far can help in improving the treatment efficiency; however, the ultimate triumph for orthodontics will be to increase the speed of

tooth movement. In recent years, numerous attempts have been made to accelerate the tooth movement. Physical approaches with low-energy laser irradiation (Kawasaki and Shimizu, 2000) and magnetic fields (Stark and Sinclair, 1987; Tengku *et al.,* 2000) as well as pharmacological approaches with the injection of prostaglandin E_2 (Yamasaki *et al.,* 1980, 1984; Leiker *et al.,* 1995) and 1,25 $(OH)_2$ D_3 (Collins *et al.,* 1988; Takano-Yamamoto *et al.,* 1992a,b) have been investigated. However, many side effects such as root resorption, pain, drug-induced side effects have been reported that have prevented their adoption in day-to-day clinical practise.

New vistas

Besides the above drawbacks, speeding up tooth movement is also plagued with the problem of 'individual variations' in treatment outcome. Individual variations in the skeletal and dental response to mechanical loading in both humans and mice are common. An answer to this vexed question may lie in unravelling of the genetic blueprint. The genetic loci for these variations are now being identified in mice and are likely to be pinpointed in humans within the next 40 years (Haven *et al.,* 2007). In some recent preliminary studies that have been performed on animal models, the physiologic and biologic markers have been well delineated. These models revealed that the presence of cytokines, such as RANKL (receptor activator of NF kappa B ligand) and OPG (osteoprotegerin) accelerate or inhibit the speed of orthodontic tooth movement (Anderson *et al.,* 1997; Kanzaki *et al.,* 2004, 2006). It has been reported that RANKL gene transfer to the periodontal tissue accelerates orthodontic tooth movement by approximately 150% in 21 days, without eliciting any systemic effects. On the other hand, OPG produced by osteoblastic or periodontal ligament cells acts as a decoy receptor for RANKL and prevents RANKL–RANK binding, thereby suppressing osteoclastic formation. Kanzaki *et al.,* (2004, 2006) concluded 'Local RANKL gene transfer might be a useful tool not only for shortening orthodontic treatment, but also for moving ankylosed teeth where teeth are fused to the surrounding bone'. However, for many reasons, the clinical application of these biological substances in humans is unlikely to be adopted in the near future, however, the theoretical model is very much in place.

Another interesting area that has evolved rapidly over the years is 'Surgical segmentation of alveolar bone to enhance tooth movement'. Corticotomy-assisted orthodontic treatment (CAOT) as it is known today is defined as a linear cutting technique in the cortical plates surrounding the teeth to produce mobilization of the teeth for immediate movement (Fitzpatrick, 1980).

The reported increase in the rate of tooth movement with corticotomy-assisted orthodontics has been attributed to a biological process denominated as regional acceleratory phenomenon. This process was described initially by Frost (1981) based on observations from bone fracture healing. However, the evidence presented in support of CAOT thus far is from case report studies only (Wilcko, 2001, 2003, 2008), which is considered weak evidence to support the purported advantages and the mechanism of action. Although recent animal studies (Ren *et al.,* 2007; Iino *et al.,* 2007; Mostafa *et al.,* 2009; Lei Wang *et al.,* 2009) have added more evidence to the effect of CAOT, more direct evidence through prospective clinical trials in humans are needed to give more credibility to this interesting prospect. Additionally, the window for expedited tooth movement after surgery lasts for approximately 2–4 months only (Lei Wang *et al.,* 2009).

Another intersecting prospect to enhance the rate of tooth movement without the added complication of surgery is through the application of 'resonance vibration'. It is based on the fact that intermittent vibrating force is mechanically more effective than a static force in changing the peridontal ligament (PDL)'s viscoelasticity, and that this effect persists over a certain period of time (Emata, 1979). At the biological level, the application of resonance vibration accelerates orthodontic tooth movement via enhanced RANKL expression in the PDL, which in turn leads to enhanced resorptive activities of osteoclasts leading to a greater tooth movement. Thus far, human trials using this principle have not been published (Nishimura *et al.,* 2008), but it appears to be a promising area of research.

Conclusion

Traditions, emotions, beliefs, commercialism, easy learning, appliance worship, all contribute to the lack of evidence-based treatment in our specialty. In this research, evidence is clouded by sampling methods, traditions, and tendencies to follow authority figures or self-proclaimed 'gurus'. Epidemiologic data also have limits with regard to understanding the mechanism of response to treatment. Therefore, scientific understanding of the mechanism of tooth movement especially in light of the current developments is essential to solid evidence-based treatment. Also as mentioned previously, in spite of the ferocious evolution of the first specialty of dentistry, the essentials of the subject still remain the same. The application of any new concept requires a firm understanding of the fundamentals of orthodontics, the theoretical framework outlining its application, and subsequent data generated by careful experimentation either proving or disapproving the concept.

Funding

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