British Journal of Orthodontics/Vol. 26/1999/29–37

Rare Earth Magnets in Orthodontics: An Overview

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Abstract. *Magnets have been used in dentistry for many years. They can be made to push or pull teeth. The force they deliver can be directed, and they can exert their force through mucosa and bone, as well as within the mouth. In orthodontics they are used for intrusion of teeth, tooth movement along archwires, expansion, retention, in functional appliances, and in the treatment of impacted teeth. New 'high energy' magnets are capable of producing very high forces relative to their size. Although magnets are potentially very useful there are a number of problems that severely affect their performance; the force produced between any two magnets falls dramatically with distance, significant irreversible loss in force is seen if the magnets are heated and a dramatic reduction in force is seen if the magnets are not ideally aligned to one another. In addition, magnets corrode badly in the mouth and a robust coating is required to protect them. This paper outlines the background to high energy magnets used in orthodontics, discusses the relevant physical and biological properties of them, and reviews their applications.*

Index words: Biocompatability, Orthodontic Applications, Physical Properties, Rare Earth Magnets.

Refereed Paper

Introduction

Magnets have been used in dentistry for many years, most commonly to aid the retention of dentures and overdentures (Javid, 1971; Federick, 1976; Gillings, 1981). In orthodontics they have been used in both research and clinical practice, particularly in the treatment of unerupted teeth (Sandler, 1991; Darendeliler and Friedle, 1994), for tooth movement along archwires (Blechman, 1985), expansion (Vardimon *et al*., 1987), fixed retention (Springate and Sandler, 1991), in the correction of anterior open bite (Dellinger, 1986), and in functional appliances (Vardimon *et al*., 1989, 1990; Darendeliler and Joho, 1993; Darendeliler *et al*., 1993). Magnets are said to have significant advantages over other materials used to move teeth such as elastic chain or push-coil as they are able to produce a measured force continuously over long periods of time. They can be made to attract or repel, and therefore to push or pull the teeth, the force they deliver can be directed, and they can exert their force through mucosa and bone as there does not need to be direct contact between them.

This overview was constructed from the work carried out over the last few years by the research team at the Eastman Dental Institute and has included a thorough hand search of the published literature.

Physical Properties

All magnets have magnetic fields around them. The field emerges from one pole of the magnet conventionally known as the north pole, and returns to the other or south pole of the magnet (Figure 1).

A magnetic field induces changes in the medium surrounding the magnet, such as air. This is called the flux density of the magnet and can be measured simply by a Hall probe. The flux produced by the magnets causes them to attract or repel other magnets, and attract other materials containing iron. Although very high forces can be produced by even small magnets, the force produced by any two magnets is inversely proportional to the square of the distance between them,

$$f \propto \frac{1}{d^2}.$$

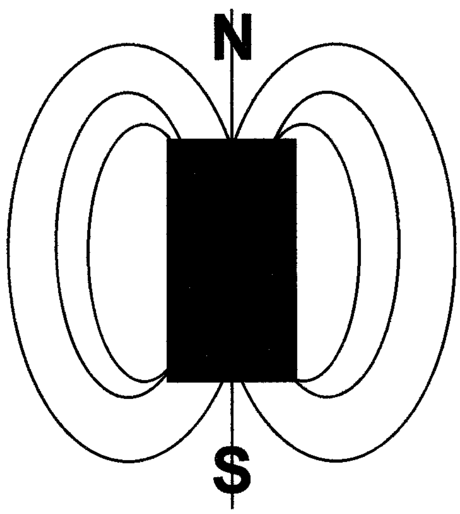

FIG. 1

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This means that the force between any two magnets falls dramatically with distance (Figure 2). Although magnets have had dental applications since the 1950s the high cost of the magnetic materials (cobalt and platinum) prevented their widespread use. This problem was overcome with the development of 'high energy' magnets in the 1970s. These magnets are capable of producing high forces relative to their size due to the property of *magnetocrystaline anisotropy*. This property allows single crystals to be preferentially aligned in one direction (along their C-axis), thus increasing the magnetism (Harris, 1990). More recently, samarium-cobalt ($SmCo_5$) and neodymium-iron-boron magnets ($Nd_2Fe_{14}B$) have been developed; the rate earth metals incorporated in these magnets significantly increases their ability to be magnetized along the C-axis. These magnets demonstrate spectacular improvements in the maximum energy product (BH_{max}), which has lead to the dramatic reduction in the size of magnets required to produce a particular magnetic flux over the last 100 years (Figure 3).

These new high energy magnets not only have the property of magnetocrystaline anisotropy, but they also have high *coercivity* (the ability of the magnet to resist demagnetization). This is produced by their intrinsic property and the manufacturing process.

There are, however, a number of shortcomings of these 'high energy' magnets. They are brittle and have low corrosion resistance (Tsutsui *et al*., 1979; Wilson *et al*., 1995; Wilson *et al*., 1997) and suffer irreversible magnetic loss if heated. As can be seen from Figure 4 there is a significant irreversible loss in flux (which is directly related to force) if the magnets are heated to even modest temperatures. In many applications, the magnets are embedded in acrylic appliances. On curing methyl methacrylate reaches a temperature of between 80 and 90°C. Embedding a small magnet in acrylic resin, therefore, could cause significant

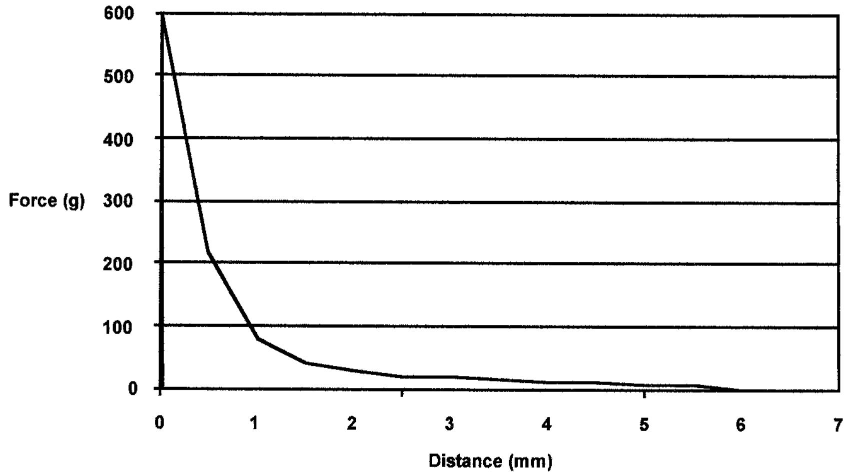


FIG. 2

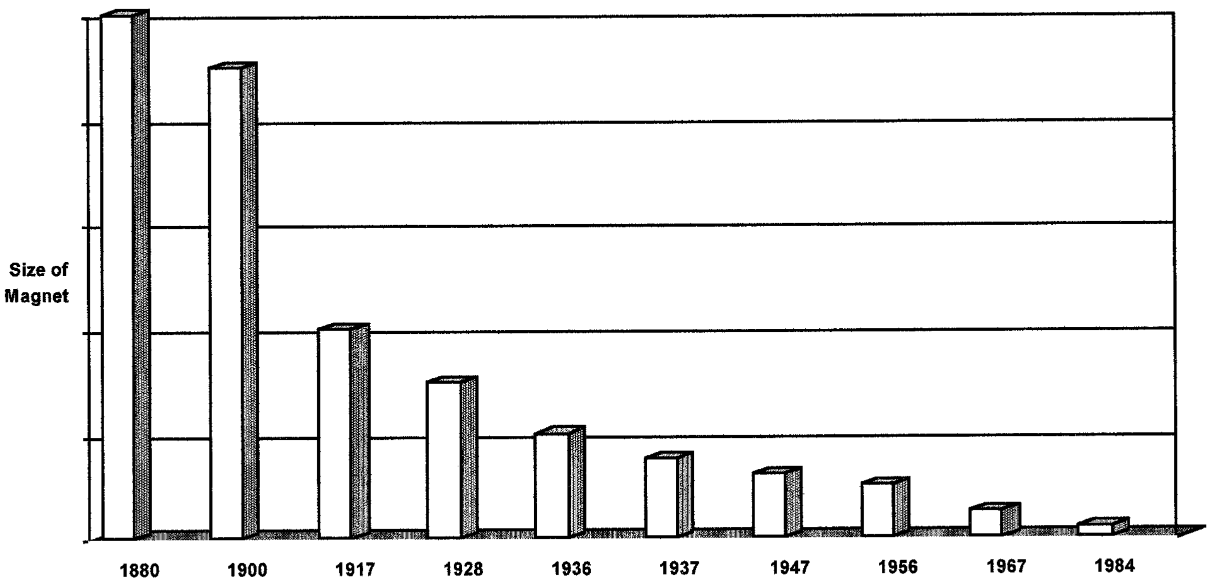


FIG. 3

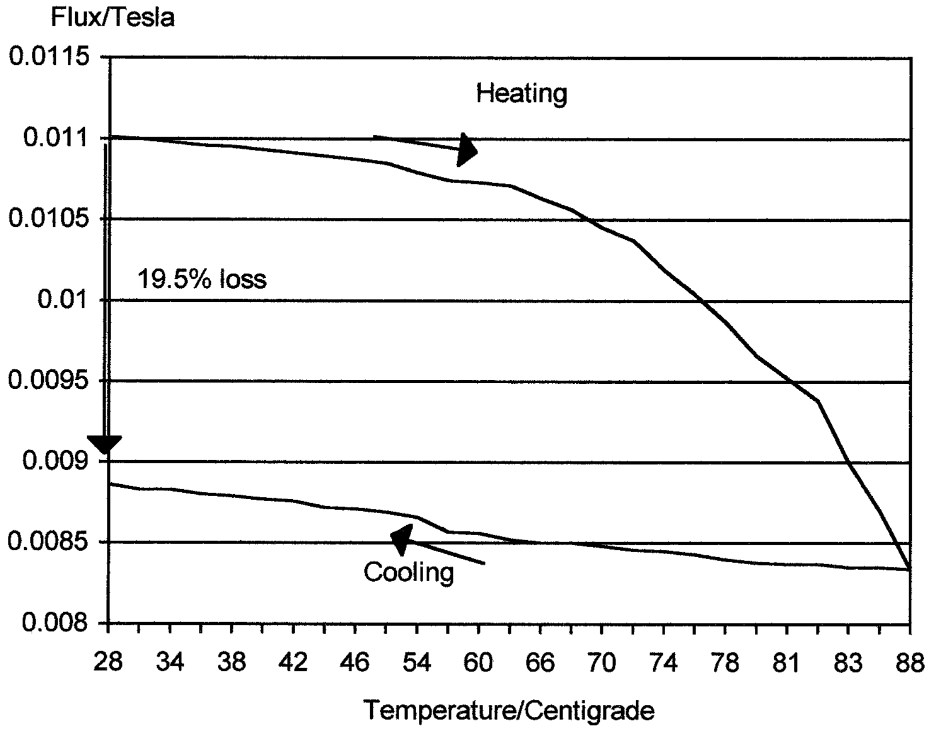


FIG. 4

amounts of flux loss due to the exothermic setting reaction of the acrylic. It is important to ensure that this loss of flux (and, therefore, force) is taken into account when preparing these magnets to move teeth.

Biological Safety

It is important to ensure, as far as it is reasonably possible, that any new material destined for clinical use should not produce any side-effects at a local or systemic level. A full evaluation must include three levels of testing. Level 1: *in vitro* testing in order to establish the toxic, allergic or carcinogenic nature of the material. Level 2: in use testing on animals. Level 3: clinical trials. Magnets used in orthodontics produce static magnetic fields. Biological safety testing of magnets containing rare earth elements has evaluated the effects of both the static magnetic field, and possible toxic effects of the materials or their corrosion products. Rare earth magnets and, in particular, those containing neodymium, are susceptible to corrosion (Vardimon and Muller, 1985) with the release of potentially harmful products. Level 1 type testing has been performed by Sandler *et al.* (1989), Bondemark *et al.* (1994a,b,c), Donohue *et al.* (1994) to evaluate the biological effects of the corrosion products. The outcome of these studies have demonstrated a range of effects from 'no cytotoxic effects' to 'mild cytotoxic effects'. Although the effects, at worse, could be considered mildly cytotoxic, it is of paramount importance to prevent corrosion from occurring. Coating the magnets with parylene (poly-para-xylene) in ultra-thin sections will produce an effective barrier to corrosion (Wilson *et al.*, 1995), although the parylene itself is not sufficiently robust to survive undamaged in the intra-oral environment (Wahab, 1997). The effects of the static magnetic field produced by the size and type of magnets used in orthodontics is controversial. In a number of level 1 type tests it has been shown that static magnetic fields can effect certain biological parameters, e.g. stimulating enzyme systems, cell proliferation/attachment, and osteogenesis (Kawata *et al.*, 1987; Camilleri and McDonald, 1993; Linder-Aronson and Lindskog, 1995). In a number of short-term level 2 type tests (Cerny, 1980; Linder-Aronson *et al.*, 1991, 1992, 1995, 1996 Camilleri and McDonald, 1993) a number of undesirable effects have been observed (e.g. epithelial thinning) which, fortunately, have shown to be reversible. There are few reports of level 3 (clinical trial) type testing. Bondemark *et al.* (1995) found that the static magnetic fields (SMF) produced by orthodontic rare earth magnets did not result in any change in human dental pulp or gingival tissue adjacent to the magnets. In a clinical, histological, and immunohistochemical study, Bondemark *et al.* (1988), found no adverse long-term effects on human buccal mucosa which had been in contact with an acrylic-coated neodymium iron boron magnets and subject to the static magnetic field. The evidence currently available from biological safety testing would suggest that the conceivable risks of harmful biological effects are negligible.

Applications of Magnetic Appliances

Tooth Intrusion

The aetiology of anterior open bite (AOB) is generally multifactorial and can be attributed to a combination of skeletal, dental, and soft tissue effects with a disproportion between the anterior and posterior upper and lower facial heights. Many treatment regimes have been advocated. Recently, removable and fixed appliances with acrylic bite blocks incorporating magnets to intrude the molars have been used. Dellinger (1986) reported on the Active Vertical Corrector (AVC). This appliance uses samarium-cobalt magnets, orientated in repulsion producing a posterior intrusive force of 600–700 g per magnetic unit. In addition, the AVC patients were instructed to wear a combined headcap and chin strap for at least 12 hours per day. It was postulated that this appliance was more efficient than usual bite block therapy due to the intermittent electromagnetic field produced by movements of the mandible which would enhance tooth movements. The three cases documented achieved a positive overbite within 4–9 months of starting AVC therapy, it was claimed that this was due to intrusion of the buccal teeth. Kiliardis *et al.* (1990), and Woods and Nanda (1988; 1989), however, have not found magnets incorporated within bite blocks any more efficient at intruding posterior teeth than bite blocks alone. Kiliardis *et al.* (1990) also concluded that the repulsive element of the magnets produced lateral mandibular movements and thus increased the risk of developing cross-bites.

Noar *et al.* (1996a,b) carried out laboratory-based experiments to examine the physical properties and performance of a fixed intrusion appliance with neodymium-iron-boron magnets used for patients with anterior open bite. This group showed that the effects of orientation of magnets on the force levels achieved between has profound effects. Figure 5 shows the results of experiments to identify the effects of different orientations of the magnets to each other, directly above each other, with one tilted with respect to the other, one skewed with respect to the other, and one edge-to-edge with the other. The results show the dramatic reduction in force if the magnets are not in perfect alignment with edge effects leading to a change from the expected repulsion into attraction in the edge-to-edge and skewed orientations. When the magnets are mounted on an articulator to simulate the culmination of these effects as may be found in a clinical situation it can be seen that force levels are further compromised.

Therefore, in summary, whilst there is evidence that bite block therapy is a useful method of treatment in AOB cases the serious deterioration in force levels if the magnets are not in perfect alignment, however, question the advantage of incorporating them in such appliances.

Retainers

Despite the success of fixed retainers to stabilize anterior spacing which are often used in orthodontics (Dahl and Zachrisson, 1991) they have a number of undesirable characteristics. They restrict access to the gingival tissues, leading to poor oral hygiene, and they often fracture because the individual teeth move independently and put excessive strain on the retainer

Micro-magnetic retainers have been suggested by (Springate and Sandler, 1991) to retain central incisors that have been brought together to close a median diastema.

After tooth movement small neodymium-iron-boron magnets are bonded with a light-cured low viscosity resin on the mesio-palatal aspect of the teeth separated during bonding by an acetate finishing strip to ensure the two magnets are not fused together. Directly bonded magnets have a number of advantages over other types of retainer. Oral hygiene can be maintained as flossing is not prevented, and there are no wires or ledges close to the gingival margins. The teeth are not splinted together, so sudden differential loading of the crowns will not cause the magnets to be dislodged and, therefore, the teeth can move completely physiologically. There are a number of problems with this approach, however; the magnets may be knocked off if the bite is very close, and the friction between the magnets may cause damage to the protective covering and, therefore, leave the magnets exposed to the oral environment where they will corrode. This technique

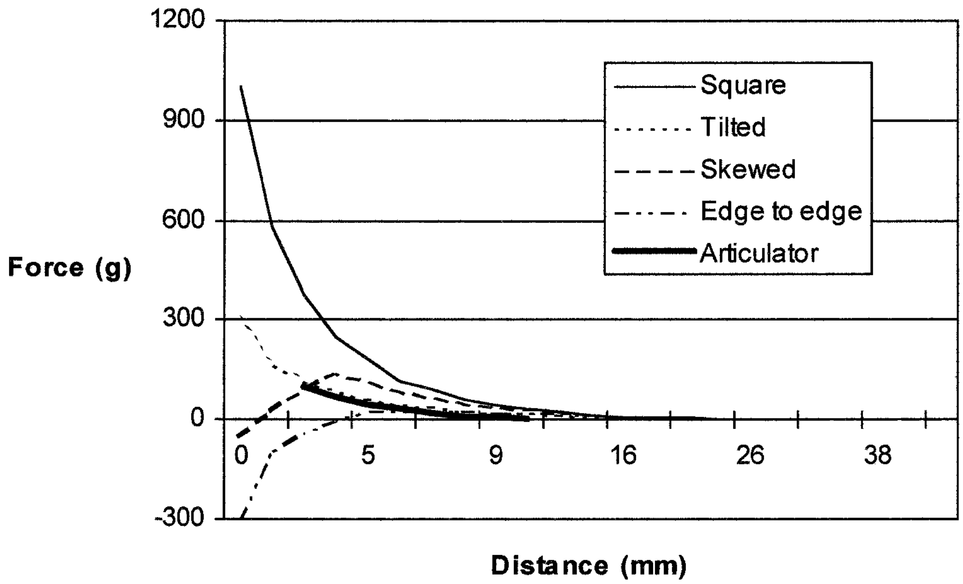


FIG. 5

for tooth retention after orthodontics, however, is potentially very useful if a robust coating that can resist damage can be developed. Unfortunately, there has not been any long-term follow-up of this technique reported and therefore it cannot be considered routine clinical practice at present.

Expansion

Intra-maxillary expansion and orthopaedic movement of the palatal shelves has been used in orthodontics for many years. Vardimon *et al.* (1987) reported on a study that looked into the effects of using samarium-cobalt magnets to provide the expansion force on monkeys. This study demonstrated that magnetic expansion does produce controlled forces over a predicted range and time. The expansion is slow compared with rapid maxillary expansion techniques (RME) and, consequently, there is less tendency for the mid-palatal suture to fracture. In addition, as the forces can be made to be more physiological it avoids the complications of the rotations of the maxilla seen in the high force appliances such as RME. Although not verified on humans magnetic expansion appliances may be useful because of the predictable, constant low forces they deliver. They are, however, likely to e quite bulky as they must be adequately stabilized and contain stout guide rods to prevent the magnets becoming out of line and causing unwanted rotational movements.

Tooth Impaction

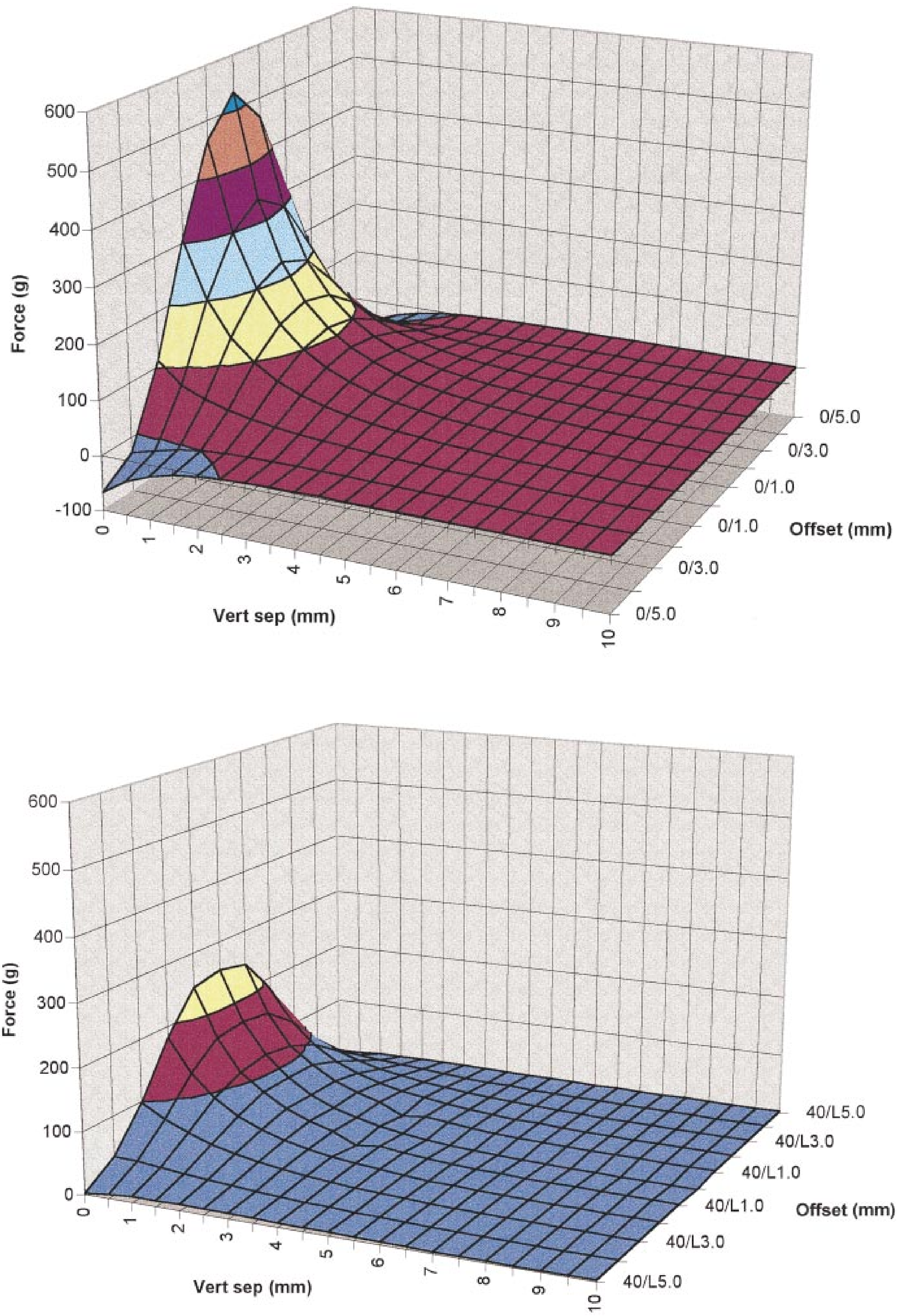
Many methods of dealing with unerupted or impacted teeth have been described. In many cases exposure alone, or exposure and applying an attachment to the tooth is used. Attachment to the tooth is normally achieved by bonding with a gold chain or stainless steel wire to the tooth. The level of force produced to move the tooth is not always easy to control, previous techniques involving pinning or lassooing the tooth has been shown to cause damage to the crown or root, and breaching the mucosa with gold chain or wire can lead to infection. A method of using small high energy magnets to provide the traction force to aid the eruption of an impacted maxillary canine has been described by Sandler (1991), and Darendeliler and Freidle (1994). Small neodymium-iron-boron magnets ($3 \times 3 \times 1$ mm) are bonded onto the unerupted canine and a second larger magnet ($5 \times 5 \times 2$ mm) is incorporated into a removable appliance in an appropriate position. The tooth is then brought into the arch. As the tooth erupts the magnet held in the appliance can be moved to direct the movement of the eruption tooth. There are a number of advantages of this technique. It is easy for both the operator, the patient does not have to attach elastics or hooks to the chain, few adjustments are needed, and the attachment is less likely to be knocked and dislodged from the tooth. The magnets can produce constant physiological forces over long periods of time and the direction of the force can be chosen by the clinician so the tooth can be encouraged to erupt into the ideal place. The are, however, an number of limitations with this approach. If the tooth is far from the oral cavity the forces may be small between the magnets. The magnets may also be subject to corrosion if their coating is damaged. In addition, great care must be taken to ensure the polarity of the magnets are correctly positioned particularly in cases where there are bilateral impacted canines to ensure the teeth move in an appropriate direction. This method of dealing with unerupted teeth has also been used on premolars and molars with good effect. A recent laboratory study (Mancini, 1996) looking at the effects of magnets used in this application has shown that the attractive force levels generated between neodymium-iron-boron magnets set in attraction are sufficient to induce the cellular and biochemical changes that are required to produce orthodontic tooth movement over a reasonable clinical range. When the angle of the pole face of the superior magnet relative to the base magnet is changed; however, the rate of decline of the force is very severe and care must be taken to ensure adequate forces are being generated between the tooth and base magnet (Figure 6a,b).

Tooth Movement

Simple tooth movement without archwires. Muller (1984) suggested that small magnets (approximately $5 \times 3 \times 1$ mm) could be used to deliver light continuous forces to close diastemas without archwires. The magnets were bonded to the labial aspect of the teeth using the indirect bonding technique. The force delivered was determined by the distance apart the teeth were and, therefore, the size of magnet bonded. Muller suggests that rotations and angulation problems can also be corrected with this technique. The author notes that the fact that the magnets produce a light continuous force that increases as the teeth get nearer is the reason the teeth move quickly. The author notes that the chairside time is low, there is no need to reactivate the appliance as long as the magnets have been correctly placed, maintaining good oral hygiene is easy, and the position of the teeth can be controlled by the position of the magnets on the teeth. The disadvantages are the difficulty in correctly positioning the magnets and the risk of inhalation if one is dislodged.

Complex intra- and inter-arch mechanics. Blechman (1985) reported the results of a pilot study where mini-magnets were used attached to Edgewise appliances to move teeth along archwires. It was suggested that the magnets can be used in attraction or repulsion to move teeth along archwires, provide Class II traction and to intrude/extrude individual teeth. Double tubes are used on the molars and the magnets mounted on sectional archwires. A base full arch is used to control the direction of the tooth movement. Blechman also reports good results with this technique how when employing magnets to deliver Class II forces and suggests that the fact that the forces between the magnets drops below clinically useful amounts when the teeth are apart negates some of the unwanted effects of Class II elastic traction. The extrusive and horizontal effects that elastics can cause are removed.

Molar distalization. Maxillary first molars have been moved distally with an intra-oral device using repelling


Force (g)
600
500
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Vert sep (mm)
0 1 2 3 4 5 6 7 8 9 10
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FIG. 6

magnets in conjunction with a modified Nance appliance. Distal movement was recorded at a rate of 3 mm in 7 weeks (Gianelly *et al.*, 1988, 1989). Similar results have been reported by Itoh *et al.* (1991).

Bondemark and Kurol (1992a,b), discussed the simultaneous movement of first and second molars using repelling samarium-cobalt magnets. Repelling force levels of 58–215 g were used and all of the maxillary molars were moved to a Class I relationship within an average time span of 16·6 weeks. However, the authors recorded a distal tipping of 8·5 and 7 degrees on the first and second molars, respectively. Bondemark *et al.* (1994), examined repelling magnets versus superelastic nickel titanium coils used for simultaneous distal movement of maxillary first and second molars. Mean distal molar movement was 3·2 mm for the supercoils and 2·2 mm for the magnets. Complaints of discomfort were more frequent on the magnet sides. The results indicated that superelastic coils are more effective than repelling rare earth magnets in molar distalisation.

Recently, Blechman and Steger (1995), have hypothesized that static magnetic fields in orthodontics generate simultaneous force fields and bio-effects which may be a possible mechanism of action of repelling, molar distalizing magnets.

Magnetic Edgewise brackets. Kawata *et al.* (1987), introduced a new force system of magnetised edgewise brackets. As a result of earlier work, claims were made that magnetic forces to move teeth were less stressful than the conventional use of springs, coils and elastics. The magnetic brackets were chromium-plated samarium-cobalt magnets soldered to the base of an Edgewise bracket which were directly bonded to the teeth and were designed to form an ideal arch shape in the maxilla and mandible at the completion of treatment. Force levels delivered to the teeth were estimated at 250 g. Bracket placement allowed mesial and distal movement of teeth only if the interbracket distance was less than 3 mm. The authors describe the treatment of a solitary patient with a Class I malocclusion.

Darendeliler and Joho (1992), described a similar system called the autonomous fixed appliance which has no brackets or arch wires, but uses individual samarium-cobalt magnets bonded to each tooth exerting a continuous force to create an ideal arch form.

Functional Appliances

Magnets have been used for the correction of Class II and Class III malocclusions. Vardimon and co-workers developed the functional orthopaedic device (FOMA II and III), which has shown positive treatment effects in monkeys (Vardimon *et al.*, 1989, 1990). In the case of FOMA II, upper and lower attracting neodymium-iron-boron magnets maintain the mandible in an advanced sagittal position. The objectives of the study were to develop an appliance capable of leaving the mandible in the advanced position and to establish a skeletal response.

The results showed that 570 g of magnetic force when the magnets were in apposition and 219 g of force if the jaws were in the rest position. Favourable changes were noted in all active cases but the FOMA II and FOMA + functional had less incisor proclination.

The first clinical experience with a magnetic activator device (MAD) for the correction of a Class II division 1 malocclusion and another device for Class III cases has recently been described (Darendeliler and Joho, 1993; Darendeliler *et al.*, 1993). Several types have been designed to deal with differing clinical problems, e.g. lateral displacement (MAD I), Class II malocclusions (MAD II), Class III's (MAD III), and open bite cases (MAD IV). The MAD IV has recently been described by Darendeliler *et al.* (1995). It uses anterior attracting neodymium-iron-boron magnets and posterior repelling magnets. The repelling magnets generate a force of 300 g each with bite opening 5·5–6·0 mm at the first molars. The two midline attracting magnets produce a force of 300 g. Three clinical cases are presented in this paper and all achieved a positive overbite rapidly.

Chate (1995) describes the propellant unilateral magnetic appliance (PUMA) in the treatment of hemifacial microsomia. This appliance uses samarium-cobalt magnets embedded in unilateral blocks of acrylic to stimulate the autogenous costochondral graft. Moss *et al.* (1993) has described the use of the twin block appliance with magnets incorporated in the treatment of Class II division 1 malocclusions. He noted that incorporating magnets into the appliance decreased the time taken to produce the sagittal changes and increased the soft tissue changes compared to those appliances without magnets. Magnets would seem to lend themselves particularly well to the two part functional systems such as the twin block appliance.

Conclusions

Magnets can be used to give predictable forces in either attraction or repulsion, they can be made small enough to suit most dental applications and can produce high forces. Their use in orthodontics, however, is limited due to a number of factors. The force between two magnets drops dramatically with distance and even at small distances apart the forces can be very low. When heated (when coated in acrylic or subjected to hot liquids) they can suffer considerable loss of flux and, therefore, force. The orientation of one magnet to another is of the utmost importance and when not in perfect alignment the force between them drops significantly. Finally, neodymium-iron-boron magnets are subject to severe corrosion in the oral environment and must be coated with a substance that is not subject to frictional wear.

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