

# The physical characteristics of neodymium iron boron magnets for tooth extrusion

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**SUMMARY** Impaction and non-eruption of teeth is a common problem encountered in orthodontics and many techniques have been proposed for the management of this condition. It has been advocated that a system utilizing magnets would supply a continuous, directionally sensitive, extrusive force, through closed mucosa and thus provide not only a physiological sound basis for successful treatment, but also reduce the need for patient compliance and appliance adjustment. This *ex vivo* investigation examined in detail the physical characteristics of neodymium iron boron magnets employed in attraction in order to assess their usefulness in the clinical situation. Attractive force and magnetic flux density measurements were recorded for nine sets of magnet pairs with differing morphologies. The effect of spatial relationship on force was assessed by varying vertical, transverse and horizontal positions of the magnets relative to each other, and by altering the pole face angles.

The data obtained suggest that magnets with larger pole face areas and longer magnetic axes provide the best performance with respect to clinical usefulness. It was possible to formulate a specific relationship between force and flux density for each magnet pair. This relationship can be used in the clinical management of unerupted teeth to predict the force between the magnets by measuring the magnetic flux density present at mucosal level. The results indicate that magnetic systems may, indeed, have a place in the treatment of unerupted teeth.

## Introduction

Magnetism is a physical phenomenon and a form of energy that can be either static or time varying. Static magnetic fields exist around ferromagnetic or permanent magnetic materials and have been used in dentistry for many years.

Neodymium iron boron (NdFeB) magnets were first used in the 1980s and produce extremely high magnetic flux densities in relation to their small size. Since the advent of these small rare earth magnets, dental applications have increased. In the field of orthodontics, the use of magnets dates back to Blechman and Smiley (1978), who tried to demonstrate intermaxillary force between the canines and molar teeth in a cat model. More recently, magnets have been used in the treatment of diastema (Muller, 1984), skeletal open bite (Dellinger, 1986; Woods and Nanda 1988, 1989; Kiliaridis *et al.*, 1990; Noar *et al.*, 1996a,b), palatal

expansion (Vardimon *et al.*, 1987), molar distalization (Gianelly *et al.*, 1988, 1989; Itoh *et al.*, 1991; Bondemark and Kurol, 1992; Bondemark *et al.*, 1994), and in conjunction with functional appliances (Vardimon *et al.*, 1989, 1990; Darendeliler and Joho, 1993; Darendeliler *et al.*, 1993, 1995; Chate, 1995). Magnetic fixed appliances have been described by Kawata *et al.* (1987), and Darendeliler and Joho (1992), and a form of magnetic retention by Springate and Sandler (1991).

Although other workers have looked at the extent and flux density of static magnetic fields generated by rare earth magnets (Bondemark *et al.*, 1995), they have not presented a relationship between force and flux density. Defining such a relationship would allow the forces being applied to the unerupted tooth to be calculated by measuring the flux density at the mucosal margin.

## Magnets and impacted teeth

A solution to treatment of impacted teeth was introduced by Sandler *et al.* (1989). Sandler and Fearn (1990), Sandler (1991), and Sandler and Springate (1991) have also described similar management of unerupted teeth. Sandler *et al.* (1989) used magnets to facilitate the eruption of a vertically impacted canine in a 12-year-old child. The tooth was surgically exposed and a NdFeB magnet bonded to its surface. A removable appliance, which housed a second NdFeB attracting magnet, was placed overlying the space available for eruption of the unerupted tooth. Although the level of attractive forces experienced with this system was not stated, after a treatment period of 4 months, a conventional bracket was bonded to aid the final alignment of the canine with a fixed appliance.

Vardimon *et al.* (1991) described the management of several unerupted teeth, including a third molar, using edgewise brackets that housed a NdFeB magnet between the wings of the bracket.

There are several advantages of using this type of approach when dealing with unerupted teeth. The magnetic attractive forces used represent a friction-free system, the force is continuous, the direction of force can be manipulated, and therefore the path of eruption can be controlled, thus minimizing the risk to adjacent teeth. A further very important advantage of this technique is that the eruptive process is through normal, closed mucoperiosteum, as the surgical flap is completely closed after the magnet has been bonded to the unerupted tooth. This will ensure that a healthy periodontium will surround the aligned tooth and that the risk of infection through the break in the mucoperiosteum through which a gold chain passes will be reduced.

This paper reports a laboratory-based study implemented to examine the exact physical properties of NdFeB magnets used in the treatment of such impacted teeth, with particular reference to the maxillary canine, and it aims to answer the following questions:

1. Is the force level between two NdFeB magnets sufficient to induce tooth movement?

2. What effect does magnet separation and spatial relationship have on the attractive force and magnetic flux density?
3. What are the effects of different magnet morphologies?
4. Is there a predictable relationship between force and flux density?

## Materials and methods

### Magnets

The magnets used in this investigation were fabricated from the alloy neodymium iron boron (Magnet Developments Limited, Swindon, UK). The magnets are commercially available for dental applications. However, the suppliers refused to supply exact details of the composition of the magnetic alloy, but it is likely that the addition of other elements, such as aluminium, dysprosium, or cobalt, was used during manufacture to improve their performance.

NdFeB permanent magnets are produced by a powder metallurgy process and provide the highest energy per unit volume of any commercially available magnetic material. The sizes used are shown in Table 1.

### Apparatus

**Force and movement equipment.** The testing apparatus was designed to measure attractive force and magnetic flux density of magnets over a range of spatial separations. The magnet pair testing regimes are shown in Table 2.

The apparatus (Figure 1) was constructed of a non-ferromagnetic material (aluminium) and consisted of a sliding table that allowed the base

**Table 1** The morphology of magnets used in this investigation.

Size	Shape	Diameter (mm)	Height (mm)
Size A	Cylinder	4	2
Size B	Cylinder	4	1
Size C	Cylinder	5	3
Size D	Box shape	5 × 5 (square)	2
Size E	Box shape	4 × 4	1.5

**Table 2** Magnet combination testing regimes.

Test 1	A combined with A
Test 2	A combined with B
Test 3	A combined with C
Test 4	A combined with D
Test 5	A combined with E
Test 6	B combined with C
Test 7	B combined with D
Test 8	B combined with E
Test 9	E combined with E

magnet to be moved to any position in the horizontal plane. Anterior, posterior, and right and left lateral positions could be determined by the use of horizontal 0.5-mm scales attached to the base of the apparatus.

The second magnet could be moved in the vertical plane by means of a cross-arm connected to a micrometer scale. This magnet could also be angled in space by virtue of the adjustable mounting attached to the cross-arm and the angle set recorded from the built in protractor.

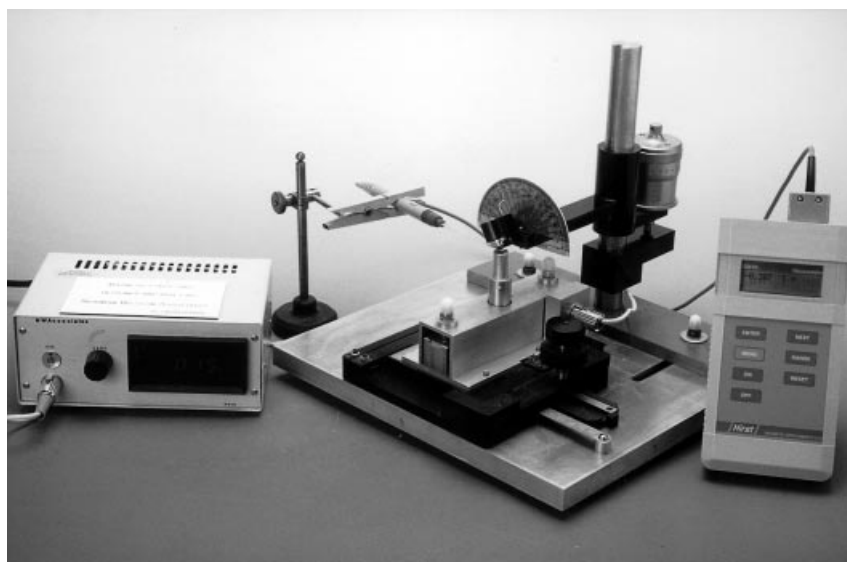
The base magnet mounting was connected directly to a load cell transducer. The signal from the load cell was digitized, and amplified and displayed as the attractive force (measured in grams) experienced by the two magnets.

In addition, a transverse Hall probe of 1-mm thickness and a GM 05 Gaussmeter (Hirst Magnetic Instruments Ltd, Cornwall, UK), was used to measure the magnetic flux density between the two magnets under investigation (Figure 1).

In order to assess the effect of the magnetic field of one magnet over the other, the Hall probe was placed in a fixed position. To avoid edge effects, flux density measurements were taken directly above the centre of the pole face of the base magnet and in contact with its surface. Noar *et al.* (1996a,b) found that maximum flux density is located at the centre of the pole face, decreasing by 31 per cent towards its edge. As the width of the probe was 1 mm, flux density measurements could only be obtained at this minimal vertical distance.

The Hall probe and Gaussmeter were calibrated to standards acknowledged by the National Physical Laboratory (1995). Measurements of magnetic flux density were recorded in milli-Tesla (mT), accurate to the nearest 0.001 T. The instrument had a zero setting capacity, which made it possible to eliminate the natural background magnetic field.

The magnets were bonded to aluminium blanks with cyanoacrylate cement and then secured into the testing apparatus prior to each test.

**Figure 1** Apparatus used in this investigation.

**Magnet pair geometry.** The magnets to be examined were placed in the apparatus so that the centres of their pole faces were in opposition and with no vertical displacement (Figure 1).

For each magnet combination, force measurements were taken as follows:

- (1) vertical pole face separation 0–10 mm in increments of 0.5 mm;
- (2) horizontal pole face separation 0–5 mm in increments of 1 mm.

For each set of measurements, the pole face of the superior magnet was angled from 0 to 50 degrees in increments of 10 degrees. As this alters the amount of pole face overlap during horizontal separations, it was necessary to distinguish between anterior, posterior, and lateral horizontal separations for each of the angular settings.

For combinations of magnets that involved a square pole face, a further horizontal separation was examined, whereby the superior magnet was moved along a line that originated in the centre of the square face and passed through its corner.

Each of these measurements were repeated three times in order to assess reproducibility. After a time period of 6 weeks 10 per cent of the readings were retaken in order to determine operator reliability.

The micrometer was accurate to  $\pm 0.001$  mm. Angular measurements were recorded in degrees using the built in protractor. When setting the angle of the superior magnet, the same reference point was repeatedly adopted in an attempt to minimize parallax errors.

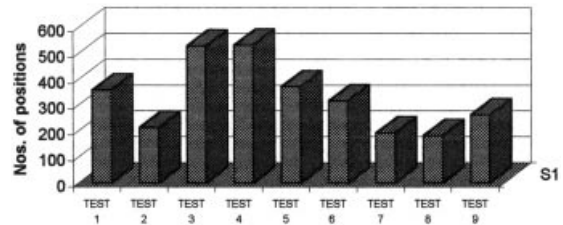
Force measurements were recorded in grams to the nearest 1 g.

## Results

### *Clinically relevant force levels*

A range of 15–200 g was chosen to represent a force that can be considered clinically relevant for tooth movement.

Each magnet combination had force and magnetic flux levels recorded over the same set of separations and angulations. Comparison was



**Figure 2** Number of positions where force levels were within the desirable limits of 15–200 g.

conducted between the nine pairs by noting all positions where desirable force levels were attained (15–200 g; Figure 2).

The results of this study show that magnet test pairs 3 and 4 were significantly better in providing the desired force levels over a greater area, whilst magnet test pairs 2, 7 and 8 appeared to produce the poorest results.

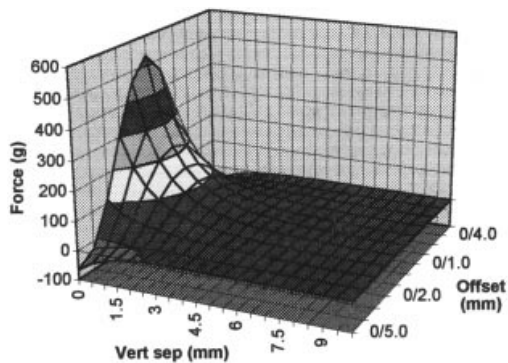
The highest recorded force and flux levels were seen during test 3. This force measurement was 532 g and the flux level was 750 mT, recorded in a position where the pole face centres opposed each other, the vertical separation was 0 mm, and a superior magnet angle of 0 degrees applied. With a vertical separation of 1 mm the force level was 226 g.

To illustrate these findings, one of the most useful magnet combinations (test pair 3) and one of the least useful (test pair 2) are graphically represented in three-dimensional mesh plot form to show how attractive force levels change with vertical separation and horizontal offset. Pole face angles 0, 20, and 40 degrees are presented (Figures 3–8). Flux level changes with varying magnet separations are shown in Figures 9 and 10.

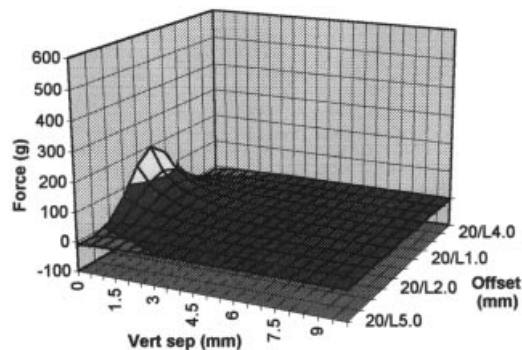
### *Force and flux relationships*

The relationships for all test pairs can be seen in Table 3. The data series pertaining to test pair 3 has been used to construct the following relationship. The data have been restricted to those parameters that relate to clinically relevant vertical separations (2–10 mm), and encompass all angulations, and all horizontal and transverse offsets.

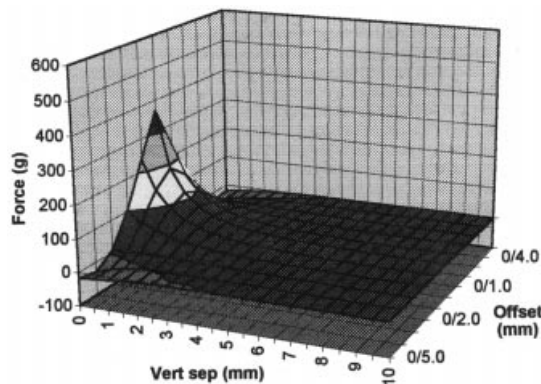




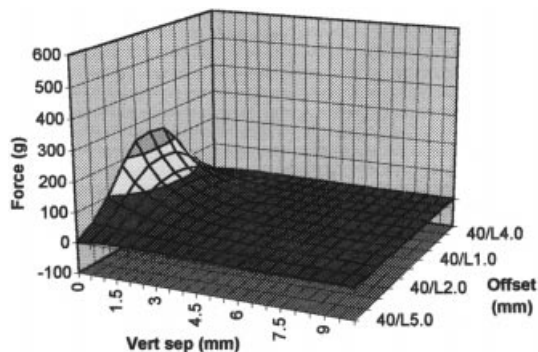
**Figure 3** Force changes of test pair 3, with no superior magnet pole face angulation during right and left lateral offsets.



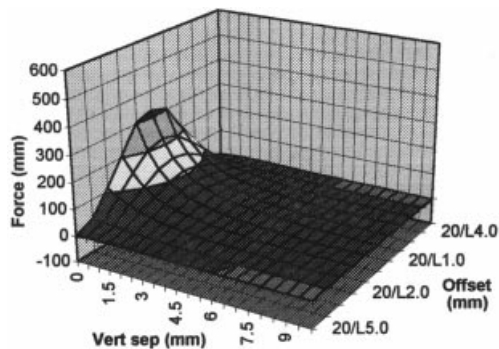
**Figure 6** Force changes of test pair 2, with superior magnet pole face angulation 20 degrees during right and left lateral offsets.



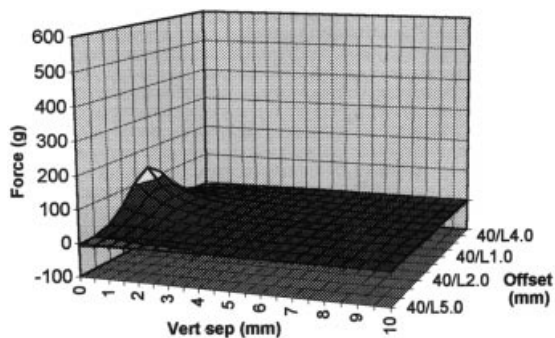
**Figure 4** Force changes of test pair 2, with no superior magnet pole face angulation during right and left lateral offsets.



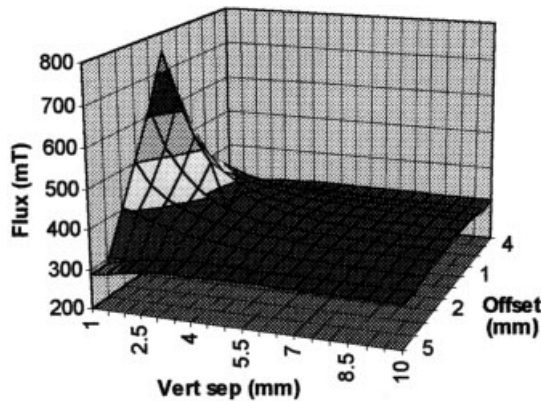
**Figure 7** Force changes of test pair 3, with superior magnet pole face angulation 40 degrees during right and left lateral offsets.



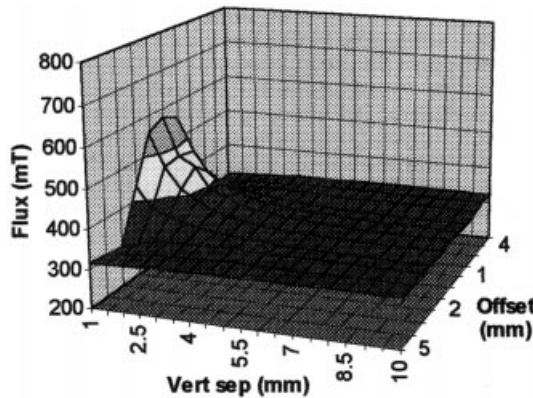
**Figure 5** Force changes of test pair 3, with superior magnet pole face angulation 20 degrees during right and left lateral offsets.



**Figure 8** Force changes of test pair 2, with superior magnet pole face angulation 40 degrees during right and left lateral offsets.



**Figure 9** Flux density changes of test pair 3, with no superior magnet pole face angulation during right and left lateral offsets.



**Figure 10** Flux density changes of test pair 2, with no superior magnet pole face angulation during right and left lateral offsets.

**Table 3** Force ( $y$ ) and flux ( $x$ ) relationships of the nine magnet pairs examined. These relationships are calculated during simple vertical separations with no horizontal offsets or pole face angulations.

Test pair	Relationship	Correlation
1	$y = -84 + 0.3402x + 0.00004x^2$	0.999
2	$y = -63.3002 + 0.23410x + 0.00013x^2$	0.999
3	$y = -183.953 + 0.60071x - 0.00008x^2$	0.999
4	$y = -130.661 + 0.59139x - 0.000021x^2$	0.999
5	$y = -49.1940 + 0.24188x + 0.00008x^2$	0.988
6	$y = -170.644 + 0.53636x - 0.00004x^2$	0.997
7	$y = -35.9282 + 0.15514x + 0.00022x^2$	0.999
8	$y = -41.1537 + 0.20020x + 0.00012x^2$	0.999
9	$y = -49.9146 + 0.23105x + 0.00022x^2$	0.999

**Table 4** Prediction of force from clinically recorded flux density readings for test pair 3 only and encompassing all three-dimensional separations.

Flux density (mT)	Force (g)	Flux density (mT)	Force (g)
300	2.8	510	78.8
310	4.6	520	78.8
320	8.1	530	79.2
330	13.0	540	80.5
340	18.8	550	82.9
350	25.2	560	86.9
360	32.0	570	92.9
370	38.9	580	101.2
380	45.6	590	112.5
390	52.0	600	127.2
400	57.9	610	145.8
410	63.1	620	167.0
420	67.7	630	197.2
430	71.5	640	231.3
440	74.5	650	271.8
450	76.8	660	319.6
460	78.3	670	375.2
470	79.2	680	439.6
480	79.5	690	513.5
490	79.4	700	597.7
500	79.1	710	693.2

A fourth order polynomial, derived in this manner is as follows:

$$y = 4053.51 - 41.2553x + 0.15229x^2 - 0.00024x^3 + 0.0000x^4$$

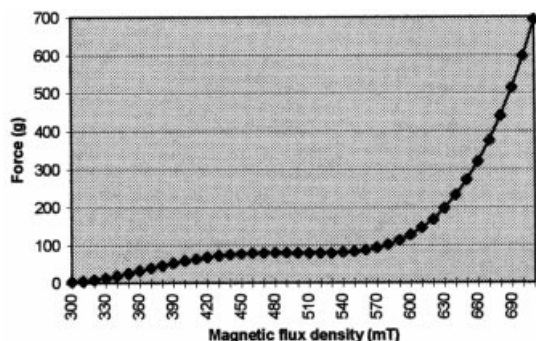
$$\text{Correlation} = 0.806$$

Table 4 and Figure 11 illustrate this relationship, and can be used in the clinical situation for predicting force levels from magnetic flux density readings.

### Statistical and analytical methods

**Means and standard deviations.** Each force and flux reading was taken three times, and mean and standard deviations calculated. It was apparent that the standard deviation of the repeated measurements was almost zero in all cases. It was therefore appropriate to base all analyses on the mean of these three readings.

**Reliability and error.** Ten per cent of the flux density and force readings were retaken after a



**Figure 11** Force and flux density relationship for test pair 3.

period of approximately 6 weeks to assess intra-operator reliability, and to quantify random and systematic error. A high level of agreement was found between the initial and repeated data set. Force levels had exact agreement in 95.3 per cent of cases and in 99 per cent of cases agreement was within 1 unit. There was a slight, but significant tendency for the differences to be negative rather than positive (the repeat reading being greater than the original). In view of this very high level of agreement and after taking further advice, no additional statistical analysis was carried out, and the data were compared directly.

## Discussion

For all magnet pairs, the magnetic attractive force and flux density decreased with increasing vertical, transverse, and horizontal separation. This is not surprising as both magnetic attractive force and magnetic flux density are forms of energy, and therefore obey the inverse square law. Increasing the pole face separation produces a rapid decline in these measured parameters. This is clinically very important as the threshold force for producing orthodontic tooth movement may not be attained, even at small pole face separations. This has also been shown by Vardimon *et al.* (1991), and Bondemark and Kurol (1992).

The effect of varying the pole face angle of the superior magnet further reduced attractive force and flux density. The rate of decline of recorded levels was more rapid when the base magnet was

posteriorly offset and the superior magnet angle was greater than 0 degrees, but reduced with anterior offsets. The explanation of these findings is that offset and angulation significantly reduce pole face overlap directly affecting the magnetic flux density and direction, and therefore force of attraction.

From the analysis of the results it is apparent that magnet test pairs 3 and 4 performed best in achieving clinically desirable force levels (15–200 g). This was probably the result of these pairings having the largest pole face areas and magnetic axis lengths of all the magnets used.

The most useful magnet test pairs still suffer rapid rates of decline with increasing angulation, and both vertical and horizontal separation, although force parameters remain useful over a greater range of orientations than is the case for the least useful pair.

Examination of the three-dimensional mesh plot diagrams depicting force relating to test pairs 2 and 3 (Figures 3–8) show that test pair 2 have lower peak heights and volumes than those of test pair 3. This is an important observation as it reflects on their suitability for clinical applications.

## Range of useful activity

Detailed analysis of force levels for test pair 3 make it possible to describe a cone of useful activity of these magnets. This cone has a height of 5.5 mm and a base diameter of 8 mm. The volume of activity is, therefore, 440 mm<sup>3</sup>. Most canines with a good prognosis for alignment will be close to or within this cone of activity. The magnet to be bonded to the unerupted tooth will itself have thickness, and this will allow the tooth to be further outside the described cone and, therefore, increase the clinical usefulness of this system.

An interesting finding of this investigation was that for all magnet pairings, repulsive forces were recorded at certain separations. Repulsion between these magnets is obviously undesirable in the clinical situation. The greatest repulsive forces were attained at vertical separations of 0 mm, combined with posterior offsets of 4 and 5 mm. The highest recorded repulsive effect was 116 g.

Repulsion occurs when similar pole faces come under the influence of each other. This is likely to be the case during a posterior offset with a superior pole face angulation. In this situation, geometry will dictate a point where pole faces of the same sign will be orientated in such a way as to affect each other and thus produce repulsion.

The clinical significance of any recorded repulsion is questionable as a situation with no vertical separation between the magnets is unlikely to occur because any base magnet placed intra-orally will be spatially adjustable.

No significant repulsion is experienced with vertical separations in excess of 2 mm, which is more clinically applicable. The phenomenon can be further limited if posterior offsets are avoided. This means that the attractive pole face of magnets bonded to unerupted teeth should always be orientated in such a way as to face the opposing pole face of the base magnet, which would be incorporated into an intra-oral appliance.

#### *Relationship between force and flux density*

Establishing a relationship between force and flux density is important from a clinical perspective, as a flux density measurement taken at chairside would enable the clinician to predict the attractive force levels operating between a magnet bonded to an unerupted tooth and a second magnet carried by an intra-oral appliance.

On initial examination of the results it became apparent that a relationship existed, which was magnet pair and orientation specific. The second order polynomial relationships already presented (Table 3) pertain to each pair of magnets separated vertically, and with no offset or superior magnet angulation. Although the correlation of these curves is nearly 100 per cent in all nine cases, the clinical relevance of these relationships is debatable because the clinician is uncertain as to the orientation of the bonded magnet and it is highly unlikely that the pairs will be ideally spatially related. To overcome these problems, the entire data set of one of the most useful magnet combinations (test pair 3), was used to construct a relationship between force and flux for that pair, over all separations and orientations

between the clinically likely vertical separations of 2 and 10 mm.

The fourth order polynomial relationship has a correlation of 0.806. It should be noted, however, that as this correlation is not perfect, some care must be exercised when attempting to predict the force levels and, therefore, the relationship should be used as a guide only.

Table 4 and Figure 11 present flux density and force relationships calculated from the fourth degree polynomial, and is intended for use in the prediction of forces from clinically-measured flux densities.

Sequential flux density readings recorded at each visit would also enable the clinician to monitor the descent of the unerupted tooth, as increases in these values would indicate that the bonded magnet is nearer the mucosa than at the previous visit and so, therefore, would be the unerupted tooth. It may also indicate if there has been a favourable angulation change of the tooth, which will negate the need for regular radiographic review to monitor progress.

#### *Clinical relevance and summary of the discussion*

The tested attractive magnet pairs showed varying levels of clinical usefulness. The best of the pairs had a superior magnet of dimensions 4 mm diameter by 2 mm high combined with a base magnet of dimensions 5 mm diameter by 3 mm high, and 5 mm by 5 mm square by 2 mm high.

It has been shown that the cone of clinically useful activity is appropriate for desired extrusive movements.

The magnets tested exhibited suitable, reliable, and predictable attractive forces, and can, therefore, be advocated in the treatment of impaction. On physical grounds, the knowledge of force and flux patterns gained from this investigation will enable the clinician to apply this system in an appropriate and efficient manner.

#### **Conclusions**

1. The attractive force levels generated between two neodymium iron boron magnets, are



sufficient to induce the cellular and biochemical changes that are required to produce orthodontic tooth movement.

2. Increasing the angle of the pole face of the superior magnet relative to the base magnet enhances the rate of decline of force and flux, particularly when combined with posterior offset.
3. Repulsion was detected for all magnet test pairs when in close vertical proximity to one another and with maximal offset, but is considered not to be clinically significant.
4. Magnet morphology will determine the clinical properties and performance of the magnet pairs.
5. Magnets with larger pole face areas and magnetic axes will be clinically more useful.
6. Neodymium iron boron magnetic attractive systems can be useful in treatments where extrusion of unerupted teeth is required. The range of useful activity can be described by a cone of height 5.5 mm and base diameter of 8 mm.
7. It is possible to predict a magnet pair specific relationship between flux density and attractive force, which can be used to identify the forces on teeth during the clinical management of unerupted teeth.

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### References

Blechman A M, Smiley H 1978 Magnetic force in orthodontics. *American Journal of Orthodontics* 74: 435–443

- Bondemark L, Kurol J 1992 Distalization of maxillary first and second molars simultaneously with repelling magnets. *European Journal of Orthodontics* 14: 264–272
- Bondemark L, Kurol J, Bernhold M 1994 Repelling magnets versus superelastic nickel-titanium coils in simultaneous distal movement of first and second molars. *Angle Orthodontist* 64: 189–198
- Bondemark L, Kurol J, Wisten Å 1995 Extent and flux density of static magnetic fields generated by orthodontic samarium–cobalt magnets. *American Journal of Orthodontics and Dentofacial Orthopedics* 107: 488–496
- Chate R A C 1995 The propellant unilateral magnetic appliance (PUMA): a new technique for hemifacial microsomia. *European Journal of Orthodontics* 17: 263–271
- Darendeliler M A, Joho J-P 1992 Class II bimaxillary protrusion treated with magnetic forces. *Journal of Clinical Orthodontics* 26: 361–368
- Darendeliler M A, Joho J-P 1993 Magnetic Activator Device II (MADII) for correction of Class II division 1 malocclusions. *American Journal of Orthodontics and Dentofacial Orthopedics* 103: 223–239
- Darendeliler M A, Chiarini M, Joho J-P 1993 Case report: early Class III treatment with magnet appliances. *Journal of Clinical Orthodontics* 27: 563–569
- Darendeliler M A, Yüksel S, Meral O 1995 Open-bite correction with the Magnetic Activator Device IV. *Journal of Clinical Orthodontics* 29: 569–576
- Dellinger E L 1986 A clinical assessment of the Active Vertical Corrector—a nonsurgical alternative for skeletal open bite. *American Journal of Orthodontics* 89: 428–436
- Gianelly A A, Vaitas A S, Thomas W M, Berger D G 1988 Distalization of molars with repelling magnets. *Journal of Clinical Orthodontics* 22: 40–44
- Gianelly A A, Vaitas A S, Thomas W M 1989 The use of magnets to move molars distally. *American Journal of Orthodontics and Dentofacial Orthopedics* 96: 161–167
- Itoh T *et al.* 1991 Molar distalization with repelling magnets. *Journal of Clinical Orthodontics* 25: 611–617
- Kawata T *et al.* 1987 A new orthodontic force system of magnetic brackets. *American Journal of Orthodontics and Dentofacial Orthopedics* 92: 241–248
- Kiliaridis S, Egermark I, Thilander B 1990 Anterior open bite treatment with magnets. *European Journal of Orthodontics* 12: 447–457
- Muller M 1984 The use of magnets in orthodontics: an alternative means to produce tooth movement. *European Journal of Orthodontics* 6: 247–253
- National Physical Laboratory 1995 Report CETM National Physical Laboratory, Teddington, Middlesex, UK
- Noar J H, Shell N, Hunt N P 1996a The physical properties and behavior of magnets used in the treatment of anterior open bite. *American Journal of Orthodontics and Dentofacial Orthopedics* 109: 437–444
- Noar J H, Shell N, Hunt N P 1996b The performance of bonded magnets used in the treatment of anterior open bite. *American Journal of Orthodontics and Dentofacial Orthopedics* 109: 549–556

- Sandler P J 1991 An attractive solution to unerupted teeth. *American Journal of Orthodontics and Dentofacial Orthopedics* 100: 489–493
- Sandler P J, Fearn J 1990 Unerupted incisors: a case report illustrating an attractive solution. *Journal of the International Association of Child Dental Health* 20: 22–25
- Sandler P J, Springate S D 1991 Unerupted premolars—an alternative approach. *British Journal of Orthodontics* 18: 315–321
- Sandler P J *et al.* 1989 Magnets and orthodontics. *British Journal of Orthodontics* 16: 243–249
- Springate S D, Sandler P J 1991 Micro-magnetic retainers: an attractive solution to fixed retention. *British Journal of Orthodontics* 18: 139–141
- Vardimon A D, Graber T M, Lawrence R, Voss L R, Verrusio E 1987 Magnetic versus mechanical expansion, with different force thresholds and points of force application. *American Journal of Orthodontics and Dentofacial Orthopedics* 92: 455–466
- Vardimon A D, Stutzmann J J, Graber T M, Voss L R, Petrovic A G 1989 Functional orthopedic magnetic appliance (FOMA) II—*Modus operandi*. *American Journal of Orthodontics and Dentofacial Orthopedics* 95: 371–387
- Vardimon A D, Graber T M, Voss L R, Muller T P 1990 Functional orthopedic appliance (FOMA) III—*Modus operandi*. *American Journal of Orthodontics and Dentofacial Orthopedics* 97: 135–148
- Vardimon A D, Graber T M, Drescher D, Bourauel C 1991 Rare earth magnets and impaction. *American Journal of Orthodontics and Dentofacial Orthopedics* 100: 494–512
- Woods M G, Nanda R S 1988 Intrusion of posterior teeth with magnets. An experiment in growing baboons. *Angle Orthodontist* 58: 136–150
- Woods M G, Nanda R S 1991 Intrusion of posterior teeth with magnets. An experiment in nongrowing baboons. *American Journal of Orthodontics and Dentofacial Orthopedics* 100: 393–400