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 at 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 Fearne (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.

<table>
<thead>
<tr>
<th>Size</th>
<th>Shape</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cylinder</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>Cylinder</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>Cylinder</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Box shape</td>
<td>5 x 5 (square)</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>Box shape</td>
<td>4 x 4</td>
<td>1.5</td>
</tr>
</tbody>
</table>
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.

**Table 2** Magnet combination testing regimes.

<table>
<thead>
<tr>
<th>Test 1</th>
<th>A combined with A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 2</td>
<td>A combined with B</td>
</tr>
<tr>
<td>Test 3</td>
<td>A combined with C</td>
</tr>
<tr>
<td>Test 4</td>
<td>A combined with D</td>
</tr>
<tr>
<td>Test 5</td>
<td>A combined with E</td>
</tr>
<tr>
<td>Test 6</td>
<td>B combined with C</td>
</tr>
<tr>
<td>Test 7</td>
<td>B combined with D</td>
</tr>
<tr>
<td>Test 8</td>
<td>B combined with E</td>
</tr>
<tr>
<td>Test 9</td>
<td>E combined with E</td>
</tr>
</tbody>
</table>

**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 ±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 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 4  Force changes of test pair 2, with no superior magnet pole face angulation 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 6  Force changes of test pair 2, with superior magnet pole face angulation 20 degrees 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 8  Force changes of test pair 2, with superior magnet pole face angulation 40 degrees during right and left lateral offsets.
A fourth order polynomial, derived in this manner is as follows:

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

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
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$^2$. 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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