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Effects of Gradually Increasing Force Generated by Permanent Rare Earth Magnets for Orthodontic Tooth Movement

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ABSTRACT

Objective: To examine the effects of gradually increasing force generated by permanent rare earth magnets for orthodontic tooth movement by using a novel experimental rat model and computer simulation.

Materials and Methods: Fifty-five male rats (age 18 weeks) were used as animal experiments. Magnetic (experimental groups) or titanium (control group) cuboids (1.5 × 1.5 × 0.7 mm) were bonded to the lingual surface of the maxillary first molars. The initial distance between materials was 1.0 mm, generating 4.96 gf (experimental group I), or 1.5 mm, generating 2.26 gf (experimental group II). Tooth movement was measured and periodontal structures were observed with microfocus x-ray computed tomography radiographs.

Results: The distance between the magnets decreased with time in experimental groups I and II ($P < .001$), whereas there was no tooth displacement in the control group. Experimental group I showed rapid tooth movement in the initial phase followed by slower tooth movement. Experimental group II showed gradual tooth movement. Horizontal sections on microfocus computed tomgraphy radiographs revealed no pathological changes, such as root resorption, on the compressed side in the experimental groups.

Conclusions: The initial light force and gradual increasing force in magnetic attractive force induced effective tooth movement in rats without inducing any pathological changes.

KEY WORDS: Rare earth magnet, Tooth movement, Attractive force, Gradually increasing force, Rat.

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INTRODUCTION Return to TOC

Theoretically, there is no doubt that continuous light forces produce the most efficient tooth movement. Continuous light force results in a relatively smooth progression of tooth movement by frontal resorption. However, traditional orthodontic appliances, which are classified by rate of decay as using continuous force (wire loops, superelastic wire), interrupted force (elastics, screws), or intermittent force (removable plates, head gear, elastics), generate progressively lighter forces as tooth movement progresses. These orthodontic appliances thus exert relatively substantial forces in the initial stages.[1]

Attractive magnetic force is light in initial phases and increases as distance between the magnets decreases, in accordance with Coulomb's Law. Magnetic force has numerous clinical advantages over traditional mechanics and has been used in various medical fields. Magnets have recently been used in medical appliances as a source of force (in artificial organs, proteases, and orthodontics), as a marker (in sensors and measuring devices),[2,3] and as an anchor (in prosthodontics).[4] In orthodontics, the first application of magnets was for tooth movement in an animal experiment.[5] Aluminum-nickel-cobalt (Al-Ni-Co),[5] samarium-cobalt (Sm-Co),[6] and neodymium-iron-boron (Nd-Fe-B) [7] magnets have been used in previous studies. However, recent progress in the field of dental materials and techniques regarding magnets has improved the biological safety and biomechanical effects.

Magnets produce a lighter force in initial stages and transmit this force without physical contact.[6] This property is considered to be very important for orthodontic applications. It is possible that an unusual response to orthodontic forces could be encountered when using a magnetic force. However, the effects of lighter forces in initial stages and increasing force have not been sufficiently investigated.

The aim of this study was to examine the effects of the gradually increasing force generated by permanent rare earth magnets on orthodontic tooth movement in rats. The effects of gradually increasing force were investigated by using light and heavy initial forces produced by differences in magnet distance.

MATERIALS AND METHODS

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Design and Computer Simulation of Magnets

Sm-Co and Nd-Fe-B magnets (cylindrical or cuboidal) were examined. The flux fields and attractive forces were simulated by three-dimensional simulation software for electromagnetic and electromechanical analysis (Maxwell 3D, Ansoft, Pittsburgh, Pa).

Animal Experiment

Fifty-five male Wistar rats (age 18 weeks) were used in this study. Cuboid magnets (1.5 mm^2 × 0.7 mm; Seiko-Sangyo, Chiba, Japan) were prepared and coated with 24-carat gold to prevent corrosion. Under general anesthesia induced by intra-abdominal injection of pentobarbital sodium salt (Tokyo Kasei Co Ltd, Tokyo, Japan), magnets were bonded to the lingual surface of the first molars with a light-cured resin adhesive (Transbond, 3M Unitek, Monrovia, Calif) (Figure 1a,b). The initial distance between magnets was 1.0 mm (experimental group I, 14 rats) or 1.5 mm (experimental group II, 14 rats). The control group (14 rats) used titanium cuboids (1.5 mm^2 × 0.7 mm; Seiko-Sangyo). An untreated group (13 rats) was fed without any appliances over the same period.

Medical Observation and Dental Impression

All rats were housed in cages (three rats per cage) in an air-conditioned and lighted environment according to the guidelines for Animal Research of Tohoku University. Before appliance placement, rats were acclimatized for 1 week and were fed a diet of ground pellets with water. Body weight was recorded and oral and systemic conditions were monitored during the acclimatization and experimental periods.

After treatment, maxillary impressions of all animals were taken at days 0, 1, 3, 7, 10, and 14 with silicone rubber impression paste (Flexicon Regular Type, GC, Tokyo, Japan) under anesthesia with inhaled diethyl ether (diethyl ether, Wako Pure Chemical Industries Ltd, Osaka, Japan), and precise plaster (New Fujirock, GC, Tokyo, Japan) models were made (Figure 2).

Measurement of Tooth Movement

Precise plaster models were scanned with a flatbed scanner (CanoScan 5200F, Canon, Tokyo, Japan) and were magnified to 1600% by digital imaging software (Photoshop, Adobe systems, San Jose, Calif). Digitized images were printed with a laser printer (microline5200, Oki Electric Industry Co Ltd, Tokyo, Japan) and were traced. The second and third molars in the maxilla were used as references for superimposition of the tracings. Distances between the mesial buccal cusps on both sides were measured with micrometer calipers based on superimpositions, and displacement was calculated. Measurement error was 0.0035 mm when 10 randomly selected samples were measured twice by a single investigator in a blind test. Errors were calculated as $E = (\Sigma d^2)^{1/2}/2n$, with E representing error, d representing the difference between two measurements, and n representing the number of samples.

Microfocus X-ray Computed Tomography Radiographs

After 0, 1, 3, 7, 10, or 14 days of treatment, rats were sacrificed with an overdose of pentobarbital sodium salt and perfused with 1.0% glutar-paraformaldehyde through the ascending aorta for 15 minutes. The upper jaws containing the first molar were excised as samples. Horizontal slices parallel to the occlusal plane were taken by microfocus computed tomography (CT) (SMX-225CT, Shimadzu Corporation, Kyoto, Japan) for each group. Slice thickness and slice height were 1.0 µm and 1.0 mm beneath the root furcation, respectively. Areas including all five roots of the first molar were selected as fields of view (Figure 2).

Statistical Analysis

Data were subjected to two-way analysis of variance (ANOVA) followed by Tukey's multiple comparison test.

RESULTS Return to TOC

Magnitude of Magnetic Force

The flux densities of Sm-Co and Nd-Fe-B magnets at an interpole distance 1.0 mm are shown in Figure 3a,b. The flux density of the Nd-Fe-B magnet was larger than that of the Sm-Co magnet. The force-distance graph of the magnets is shown in Figure 4. The magnitude of the Sm-Co and Nd-Fe-B magnets decreased with interpole distance, in accordance with Coulomb's Law. The magnitude of Nd-Fe-B magnets was larger than that of Sm-Co magnets at all distances.

On the basis of the computer simulation results, Nd-Fe-B magnets were selected for use in the animal model. The cuboid magnets used in this experiment generated 4.96 gf at 1.0 mm and 2.26 gf at 1.5 mm (Figure 5). The initial load in experimental group II was approximately half that in experimental group I. The flux density of the magnets (1.5. × 1.5 × 0.7 mm) used in this experiment at 1.0 mm and 1.5 mm are shown in Figure 3c,d.

Amount of Tooth Movement

Mean weights and standard deviations are shown in Figure 6. There were no significant differences between the groups by two-way ANOVA followed by Tukey's multiple comparison test. Animal weight in each group showed a gradual increase within normal limits. Systemic and oral examination revealed no abnormal findings, except a slight local inflammation caused by the physical presence of the magnets. Magnets on both sides in experimental groups I and II gradually approached one another and made contact during the experimental period (Figure 1c). The time courses of tooth movement in experimental groups I and II are shown in Figure 7. There was no tooth displacement in the control group. The amount of tooth movement on days 1 and 3 in experimental group I was significantly larger than that in experimental group II ($P < .05$).

Pathological Findings of Periodontal Tissues

Horizontal sections of microfocus CT radiographs from the untreated group, experimental group I, experimental group II, and control group on day 14 are shown in Figure 8. The periodontal tissues in all groups showed no pathological changes, such as root resorption.

DISCUSSION Return to TOC

Management of applied force and duration is important for desirable and smooth progression of tooth movement. In orthodontic treatment, elastic, spring, or wire forces have been used as the main sources of force for tooth movement. The orthodontic force generated by such appliances decreases gradually with time and tooth movement.[1] On the other hand, desirable orthodontic tooth movement requires the application of continuous light force. However, except for orthodontic superelastic wire,[8,9] most devices apply decreasing force. The force-distance curve for magnets is hyperbolic, which is characteristic of Coulomb's Law. The attractive force of magnets is thus characterized by light force in initial phases, followed by gradual increases.

The initial phases of tooth movement are considered to be important because major environmental changes occur.[10] The present animal experimental model was designed to exert light or heavy force in initial phases according to magnet distance. Light forces induce the smooth progression of tooth movement by frontal resorption. On the other hand, heavy forces lead to necrosis of the periodontal ligament and rapidly developing pain and produce undermining resorption of the alveolar bone near the affected tooth.[1] In dog experiments, light forces resulted in a smaller hyalinized zone on the pressure sides.[11] There was more resorption of the root surface with the heavy force when compared with the light force.[12] The force magnitudes used in this study were smaller than the applied forces in previous rat experimental studies.[13,14] In the present study, computer simulations confirmed a twofold difference in the magnitude of attractive force between the two experimental groups. Rapid and gradual tooth movements in initial phases were observed in these two groups. Even lighter forces are able to stimulate periodontal tissue and subsequent bone resorption, though initial tooth movement may simply be displacement without bone resorption.

The effects of increasing force have not been examined in orthodontic tooth movement. Attractive magnetic force increases according to magnet size and distance. In orthodontic practice, the goal is to produce as much tooth movement as possible by frontal resorption without hyalinized or necrotic changes.[1] Heavier forces are undesirable because of the resulting hyalinized or necrotic changes in periodontal tissue.[15] In this study, tooth movement in experimental groups was observed without orthodontic problems such as root resorption, as confirmed by morphological examination by microfocus CT. Moreover, it is interesting that greater initial magnet distance, which is characterized by initial light force and gradually increasing force, gave gradual and smooth displacement without rapid changes. After the initial response to light force, effective tooth movement may be induced by increasing the force. Thus, lighter initial forces provide gentle stimulation to periodontal tissue, and gradually increasing force up to effective loading magnitudes may be suitable for biological reactions in tooth movement. Practically, magnets can be applied to avoid the increases to excessive magnitudes of force, which result in tissue damage, by controlling magnet shape, size, and distance.

In vitro Nd-Fe-B magnets showed greater biocompatibility than did Sm-Co magnets.[16] In previous examinations, animal experimental models confirmed the biological safety of magnets in oral tissues adjacent to the magnetic field and all internal viscera.[5,17–19] The oral cavity environment is not chemically or physically stable. The present study showed no pathological changes in the oral mucosa.

For orthodontic appliances, it is desirable that magnet size be as small as possible for functional and esthetic reasons.[6] However, existing orthodontic appliances for dental arch constriction inevitably cause esthetic dissatisfaction and some degree of discomfort for patients. Despite the range of appliances for dental arch expansion,[20–25] there are few effective appliances for dental arch constriction.[24,25] In the present study, dental arch constriction was effectively induced in this rat model. The use of new Nd-Fe-B magnets may allow further reductions in the size of orthodontic appliances. Magnetic forces are predictable without direct contact or friction. Thus, magnets produce an appropriate magnitude of force for orthodontic tooth movement, and it is not necessary to maintain a physical connection. Magnets may thus become an important part of orthodontic treatment.

CONCLUSIONS Return to TOC

- The initial light force and gradual increasing force in magnetic attractive force induced effective tooth movement without pathological changes in rats. Magnets can be applied to various orthodontic appliances.

ACKNOWLEDGMENTS

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FIGURES Return to TOC

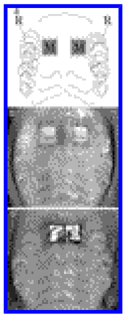

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Figure 1. (a) Schematic view of applied magnets in rat maxilla. (b) Initial condition after application of magnets to rat maxilla. (c) Rat maxilla in experimental group II at 21 days after application. M indicates magnet coated with gold; R, light-cured resin to bond magnet or titanium to the medial, buccal, and lingual surfaces of first molars

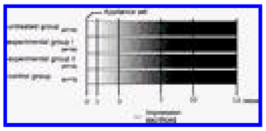

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Figure 2. Experimental procedure

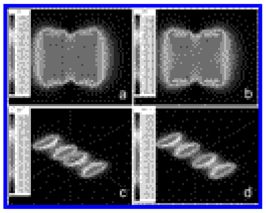

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Figure 3. Flux field and density of cylindrical magnets (Φ3.0 × 2.0 mm) at 1.0 mm interpole distance. (a) Samarium-cobalt magnet. (b) Neodymium-iron-boron (Nd-Fe-B) magnet. Flux field and density of Nd-Fe-B magnet used in this experiment: 1.5 × 1.5 × 0.7 mm. (c) 1.0 mm interpole distance. (d) 1.5 mm interpole distance

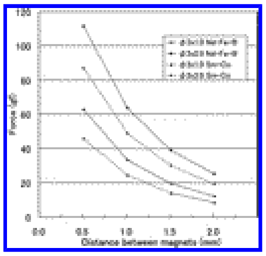

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Figure 4. Force-distance graph for cylindrical neodymium-iron-boron and samarium-cobalt magnets (Φ3.0 × 2.0 mm, Φ3.0 × 1.0 mm)

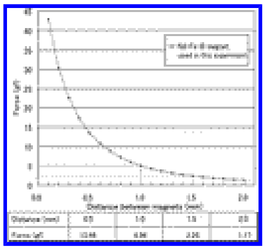

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Figure 5. Force-distance graph for cuboid neodymium-iron-boron magnets (1.5 × 1.5 × 0.7 mm) used in this experiment

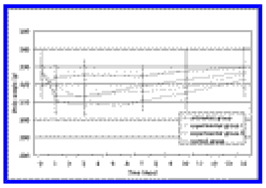

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Figure 6. Time course of body weight in control group, experimental group I, and experimental group II

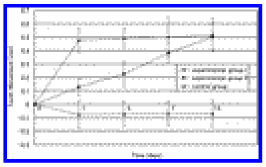

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Figure 7. Time course of tooth movement in control group, experimental group I, and experimental group II

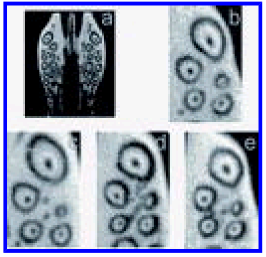

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Figure 8. Horizontal sections on microfocus x-ray computed tomography radiographs of the maxillae at 14 days after application of magnets. Slice thickness was 1 μm and slice height was 1.0 mm ± 1.0 mm from root furcation (70 kV, 200 μA). (a) Slice section of maxilla, box indicates magnified area. (b) Untreated group. (c) Control group. (d) Experimental group I. (e) Experimental group II

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