The Effects of a Static Magnetic Field on Bone Formation Around a Sandblasted, Large-Grit, Acid-Etched–Treated Titanium Implant

Richard Leesungbok, DMD, MSD, PhD
Su-Jin Ahn, DMD, MSD, PhD
Suk-Won Lee, DMD, MSD, PhD
Geon-Ho Park, DMD, MSD, PhD
Joo-Sung Kang, DMD, MSD
Jung-Joo Choi, DMD, MSD

The purpose of this study was to compare the bone formation around commercial sandblasted, large-grit, acid-etched (SLA)–treated titanium implants with or without a neodymium magnet in a rabbit tibia through histomorphometric analysis. Commercial SLA-treated implants with or without neodymium magnets were placed in 10 rabbits. After incising the flat part of the rabbit’s tibia and installation of the specimens of titanium implants, the nonmagnet group was stitched without magnet insertion. On the other hand, the magnet group was inserted with neodymium magnet, fixed with pattern resin, and stitched. At 3 and 6 weeks after surgery, the animals were sacrificed, and the specimens were obtained. Undecalcified specimens were prepared for histomorphometric analysis of the bone-to-implant contact ratio (BIC) and bone volume (BV). The histomorphometric findings of the cortical bone showed that the mean BVs of the magnet group (3 weeks, 75.99%; 6 weeks, 82.94%) were higher than those of the nonmagnet group (3 weeks, 74.58%; 6 weeks, 78.75%), but there were no significant differences between the 2 groups ($P > .05$). In the marrow bone, the mean BICs of the magnet group (3 weeks, 10.36%; 6 weeks, 10.41%) were higher than those of the nonmagnet group (3 weeks, 6.41%; 6 weeks, 7.36%). After 3 weeks of installation, there was a significant difference between the 2 groups ($P < .05$). In rabbit tibia, the SLA-treated titanium implants with a neodymium magnet can trigger faster early peri-implant bone formation than those without a magnet.

Key Words: static magnetic field, early peri-implant bone formation, histomorphometric analysis, SLA-treated titanium implant

INTRODUCTION

Dental implants were invented to liberate patients from the effects of the loss of teeth and alveolar bone around it on mastication, esthetics, and pronunciation. They have advanced rapidly after the hypothesis was proven that osseointegration occurs directly when an implant and osseous tissue integrates without any soft-tissue intervention. Nevertheless, patients still experience a long period of inconvenience to allow the superstructure of a prosthetic appliance to be fully functional for mastication after implant installation. The healing process of each patient can differ significantly from 6 weeks to 6 months according to their bone density. Therefore, several attempts have been made to find the right solution for patients experiencing difficulties during the osseointegration process.
process after implant installation by shortening the healing process by boosting the growth and development of the surrounding bone formation. Pure titanium has excellent mechanical characteristics and biocompatibility with the human body but lacks the ability to induce new bone formation, which results in a long healing time. Therefore, a variety of methods have been reported to enhance the osseointegration process using the shape of an implant, rough surface, and various surface treatments to boost bone formation and expand its directly contacted areas of the implant and bone structure after implant installation. Many new surface treatments for implants have been developed, for example, the resorbable blast media surface treatment method uses calcium phosphate particles as blast media, which are sprayed onto the surface of a titanium implant; the sandblasted, large-grid, acid-etched (SLA) method, which uses aluminum oxide (Al$_2$O$_3$) or titanium oxide, which is sprayed on the surface as a primary step, followed by hydrochloric acid/sulfuric acid as a second step; and a titanium plasma spray method.

Besides the surface treatment method, biophysical stimulation, such as an electromagnetic field, low-intensity pulsed ultrasound, and low-level laser have been used for osteogenesis and bone growth around an implant as another method. Among these methods, electromagnetic field stimulation of biological systems, such as organs, tissues, and cellular and subcellular levels, has been studied extensively. For example, Skerry et al observed a decrease in resorption on the bone surface in response to osteoclasts or their precursors. Therefore, it is unclear if the maintenance or increase in bone mass in response to electromagnetic stimulation is related to the up-regulation of the number or function of osteoblasts, a decrease in osteoclast activity, or a combination of both. Electromagnetic stimulation can also increase bone formation by enhancing the recruitment, proliferation, and differentiation of osteoprogenitors and chondroprogenitors.

Magnetic fields can be divided into pulsed electromagnetic fields (PEMFs) and static magnetic fields (SMFs). The effects on the bone of 2 magnetic fields are somewhat different. PEMF generates an electric current in the tissue, whereas SMF creates only a magnetic field. Most studies of magnetic fields after the installation of implants used PEMF. However, it needs a specific instrument such as a PEMF generator for the application PEMF and takes stimulation time per day, so it is very difficult to use in clinical situations. On the other hand, SMF can be used more easily in clinical situations if the magnet size is small enough to be placed at the implant and can generate a suitable magnet field.

This study was designed to evaluate the possibility of the clinical use of an SMF in implant treatment. A neodymium magnet was inserted in the SLA-treated implants. The bone volume (BV) and bone-to-implant contact ratio (BIC) were measured to study the effect of the SMF on bone formation around the implant during the initial bone-healing process. The research hypothesis of this study was that there is a difference in the BIC and BV of the implants, which is the inserted neodymium magnet.

**MATERIALS AND METHODS**

**Animals and implant specimens**

Ten New Zealand white rabbits with an average weight and age of 2.8 kg and 6 weeks, respectively, were used in this study. The implants used in this study were screw-shaped, 3.4 mm in diameter, and 5.0 mm in length (Dentium Co, Suwon, Korea). The implant surface was treated with SLA (Figure 1). These implants were divided into 4 groups according to the presence of a magnet and predetermined healing period. Each group contained 10 specimens, yielding a total of 40 specimens.

**Neodymium magnet**

A neodymium magnet (Ne2Fe14B, Qingdao Qiangsheng Magnets Co, Shandong, China), 2.0 mm in diameter and 1.0 mm in length, was used in the magnet group. Stainless steel was used as a protecting seal to prevent exposure of the biological tissue to the neodymium magnet. The permanent magnet had a magnetism of 15.34 mT during the experiment, which was measured around the top area of the implant.

**Magnetic strength measurement**

The neodymium magnet was placed inside the titanium implant, and the strength of the magnet fields was measured 10 times at the first micro thread of the implant, first thread region, and the
third thread of the implant using a Gaussmeter (TM-601, Kanetec Co, Tokyo, Japan).

**Surgical procedure**

The animals were preanesthetized with an intravenous injection of a mixture of 25 mg/kg ketamine hydrochloride (Ketara, Yuhan, Seoul, Korea) and 25 mg/kg xylazine (rompun, Bayer Korea, Seoul, Korea). A total of 0.5 mL of 2% lidocaine (1:100 000 epinephrine; Yuhan, Seoul, Korea) was then applied to the surgical site to provide local anesthesia. Before the actual operation, iodine liquid and 70% alcohol was used for sterilization around a shaved tibia. Four implants were placed in the rabbit tibias using a traditional surgical implant clinical method. All surgical processes were performed through the perfusion of a physiological saline solution to prevent overheating. A newly designed cover screw (patent No. 08–92400, Korean Intellectual Property Office, Korea) was attached to the implant’s internal hex area. For the magnet group, a neodymium magnet was placed on a cover screw, and its placement was fixed through the overbite with pattern resin (GC Co, Tokyo, Japan). For the nonmagnet group, only pattern resin was used for the overbite without a magnet (Figure 2). The fascia and skin was sutured using Vicryl 4-0 (Ethicon GmbH, Norderstedt, Germany). After surgery, 2.0 mL of cephradine (Dae Han New Pharm, Seoul, Korea) was used once per day for 1 week to prevent infection, and 0.2 mL ketoprofen (Unibiotech, Seoul, Korea) shots were administered for pain relief and to reduce inflammation. At the end of the experimental period, the animals were sacrificed by the intravenous administration of a high dose of ketamine hydrochloride (Yuhan, Seoul, Korea) at weeks 3 and 6 after surgery. This experiment was approved by Chungbuk University Animal Testing Research Support Center of the Institutional Animal Care and Use Committee.

**Processing of bone samples**

Tissue sections that included samples from the surgical site were obtained immediately after sacrifice. Before depletion, parts of the tibia and
histotome were collected around the surgical region and fixed with a 10% formalin solution (diluted with 1XPBS buffer). Each tissue sample was labeled. Subsequently, the sample was fixed for 2 weeks in buffered neutral formalin (Sigma-Aldrich Co, St Louis, Mo) solution. The sample was then dehydrated in graded series of ethanol (70%, 80%, 90%, and 100%). The completely dehydrated tissue samples were infiltrated with a mixture (1:3, 1:1, 3:1 ratio) of alcohol and Technovit 7200 resin (Heraeus Kulzer GmbH, Wehrheim, Germany). The ratio was increased each day. To complete the process, the final Technovit 7200 undiluted solution was infiltrated after the solution had been shaken in a vacuum for 1 week. The fully infiltrated tissues were labeled on an embedding mold, and the implant was set downward for actual embedding. Subsequently, a fully embedded mold was inserted into the UV embedding system (EXAKT 520, EXAKT Apparatebau GmbH & Co KG, Norderstedt, Germany), and the resin was stiffened overnight. The stiffened disc was then created into a tissue slide on the center of the implant using an EXAKT diamond cutter (EXAKT 300, EXAKT Apparatebau GmbH & Co, KG). A tissue piece was cut into 400-μm sections, and an EXAKT grinding machine (EXAKT 400CS, EXAKT Apparatebau GmbH & Co KG, Norderstedt, Germany) was used to grind the piece to a thickness of 15 μm so that tissue samples could be created. The tissue samples were dyed with hematoxylin-eosin, and digital film shots of all tissue discs were taken using a DP70 microscope with a digital camera (Olympus America Inc, Melville, NY) and BX-50 fluorescence microscope (Olympus America Inc).

**Histomorphometric analysis**

To measure the BV between micro threads, 3 consecutive segments of micro threads were connected through its peaks, and the area of the surrounding micro threads on the implant was calculated. Next, the existing relevant bone areas were calculated, and the bone areas between the micro threads were measured using the calculated ratio (Figure 3). To measure the BIC, located below the compact bone, the total length of the threads starting from the cancellous bone area was measured first. The measured numbers in percentages were then obtained using the subtracted value of the threads of the noncontacted bones (Figure 4).

**Statistical analysis**

All of the data management and assessments were performed using a statistical program, SPSS version 12 (SPSS Inc, Chicago, Ill). The data were analyzed using a 1-way analysis of variance, followed by Tukey’s HSD test ($\alpha = .05$). $P$ values of less than .05 were considered significant.

**RESULTS**

**Strength of magnetism**

The mean magnetism of the first micro thread of the implant, first thread region, and third thread of the implant measured 10 times were 15.34 ($\pm 0.94$) mT, 13.30 ($\pm 1.13$) mT, and 2.15 ($\pm 0.41$) mT, respectively.

**Histomorphometric analysis**

The BV between all the micro threads was calculated. After 3 weeks’ calculation, the mean BV in the nonmagnet and magnet group was 74.58% ($\pm 12.12$%) and 75.99% ($\pm 10.26$%), respectively, but the difference was not significant ($P > .05$). Similarly, after 6 weeks, the average result for the nonmagnet and magnet group was 78.75% ($\pm 14.48$%) and 82.94% ($\pm 9.55$%), showing no significant difference between the 2 groups ($P > .05$). As a final result, the calculation and elapsed time for both 3 and 6 weeks after surgery for the 2 groups were similar ($P > .05$; Table 1). After 3 weeks, the magnet group has a significantly higher mean BIC than the nonmagnet group, 10.36% ($\pm 3.07$%) and 6.41% ($\pm 2.80$%; $P < .05$). After 6 weeks, the mean BIC was similar in both groups, 7.36% ($\pm 3.79$%) and 10.41% ($\pm 3.59$%) in the nonmagnet and magnet group ($P > .05$). Therefore, the BIC after 3 and 6 weeks was similar in the 2 groups ($P > .05$; Table 2).

**DISCUSSION**

In the present study, we evaluated the effect of an SMF on bone formation around an SLA-treated titanium implant in a rabbit tibia. Our results confirmed the hypothesis as there was a significant increase in the BIC around the cancellous bone...
observed after 3 weeks’ exposure to the magnetic field.

Neodymium magnets have a strong permanent magnetism despite their small size. This powerful magnet is with a mixture of neodymium, iron, and boron. The magnet is created through a particle arrangement of a mixed powder in a mold, which then undergoes a pressure sintering process. Although this source loses its characteristics over 80°C and is completely lost at 312°C, the high magnetic quality of this magnet is useful for lighter and cheaper usage compared with samarium-cobalt magnets. In the present study, a small but powerful neodymium magnet was placed in the implant’s cover screw to acquire sufficient magnetism during the experiment.

Osteoblasts and osteoclasts have intimate effects on bone formation. Either directly or indirectly, these 2 different cells have important effects on bone tissue for bone healing and remodeling. The SMFs have been used practically for bone formation in medical research under a weak magnetic force for a long period.

Yan et al.\textsuperscript{20} inserted a 5-mm magnet stick of 180 mT into a mouse femur for 12 weeks and found that the femur with a nonmagnetic force stick had a lower Ca concentration and bone mineral density than the femur with a magnetic force stick.
inserted. Xu et al\textsuperscript{21} examined an ischemic bone model of a mouse and reported that the insertion of a 50-mT magnetic force stick increased blood circulation, which helped increase the rate of bone formation. Camilleri and McDonald\textsuperscript{22} examined the effects of a 100-mT magnetic force on a mouse’s sagittal suture that was exposed for 1 to 10 days to determine if there is any loss in thymidine uptake after 3 days’ exposure to the magnetic force. Bruce et al\textsuperscript{15} examined the healing process of a fracture on a rabbit’s radius for 4 weeks and reported that a thicker and stronger trabecular bone was formed around the fractured area exposed to a magnetic strength of 22 to 26 mT under SMF observation. Tengku et al\textsuperscript{23} exposed a mouse to a 10- to 17-mT permanent magnet for 1 to 14 days and observed corrected teeth arrangement. They reported that there was more uptake on the corrected teeth arrangement than the dental root during 7 days of observation, and the periodontal ligament space was greatly extended. Kotani et al\textsuperscript{24} examined a pallet inserted in a mouse under 8 T of bone morphogenetic protein–2 for 60 hours. The results showed that bone growth was much larger around the pallets than in the control group.

In the field of dentistry, many experiments have been carried out to examine the impact of electromagnetic stimulation or fields on bone formation and growth. The initial researches were used practically for orthodontics or periodontics.\textsuperscript{16,25–27} These studies have been expanded to implant fields and have shown a decrease in duration of osseointegration of an implant using PEMF and SMF for bone formation and growth around the implant.

In this experiment, the bone area and new bone formation at the inferior part of a compact bone and the BIC between the micro threads of the disc area of the implant were calculated. The changes in bone formation through magnetism were examined to determine the benefits in oral implant or bone graft. The results showed that there were no significant changes in the BV in between the micro threads of both groups after 3 and 6 weeks. This result is predictable because of the micro threads of the implant being placed in compact bone in both the magnet and nonmagnet groups. On the other hand, an inferior part of new bone formation and the implant’s bone contact ratio of both the magnet and nonmagnet group showed a significant difference after 3 weeks. This is due to the impact of magnetism at the new bone formation at the inferior part of the compact bone during the initial installing process. However, this appeared to have no effect or significance after 6 weeks, showing that magnetism has an effect only in the initial stages. Therefore, using cover screw–type magnets seems to be more useful for the initial stages of bone formation. If it is possible to perform more studies of the effects of magnetic fields to determine the optimized magnetic field strength and if this magnetic field can be applied equally around the implant, such research will make it possible to reduce the healing time and will have a benefit on the early loading of the implant.

There are 2 major issues to consider when using magnets, which can have harmful side effects on the human body. According to the International Commission on Non-ionizing Radiation Protection (ICNIRP), the recommended time-weighted average of the magnetism of a fully exposed body during working days of professional workers is less than 200 mT, with a ceiling value under 2 T and limbs under 5 T. For ordinary people, less than 40 mT is recommended. In addition, less than 0.5 mT is recommended for individuals equipped with car-

### Table 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean (SD)</th>
<th>Tukey Analysis</th>
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<tr>
<td>Nonmagnet, 3 wk</td>
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<tr>
<td>Magnet, 3 wk</td>
<td>75.99 (10.26)</td>
<td>A</td>
</tr>
<tr>
<td>Nonmagnet, 6 wk</td>
<td>78.75 (14.48)</td>
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</tr>
<tr>
<td>Magnet, 6 wk</td>
<td>82.94 (9.55)</td>
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*Groups with same uppercase letters were not significantly different according to Tukey’s multiple comparison at \( P < .05 \).

### Table 2

<table>
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<th>Tukey Analysis</th>
</tr>
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</tr>
<tr>
<td>Magnet, 3 wk</td>
<td>10.36 (3.07)</td>
<td>B</td>
</tr>
<tr>
<td>Nonmagnet, 6 wk</td>
<td>7.36 (3.79)</td>
<td>A</td>
</tr>
<tr>
<td>Magnet, 6 wk</td>
<td>10.41 (3.59)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Groups with same uppercase letters were not significantly different according to Tukey’s multiple comparison at \( P < .05 \).
diac pacemakers. In this particular experiment, a highest average of 16.3 mT was used for the implant teeth ridge, thereby passing the ICNIRP-recommended average, making it safe for use. However, careful attention is needed for patients equipped with cardiac pacemakers, even though it should be safe because the installed implant is more than 10 cm away from the heart. Bondemark et al demonstrated that a coated samarium-cobalt magnet of 10 mT to 15 mT on teeth for 8 weeks of observation had no noticeable effect on nerve tissue and gum tissue after extraction. In addition, an acryl-coated 80- to 140-mT neodymium magnet was adhered to the buccal membrane for 9 weeks of observation. Clinically, there were no abnormal side effects on the surface. Another issue is whether the magnet itself has harmful effects on the human body. Experiments on the human body have shown that there were some cytotoxic effects caused by rare-earth magnet corrosion, but the problem was solved by coating the magnet. Therefore, the solution is to seal the magnet with safe and strong materials by lamination or encapsulation.

A limitation of the present study is that we examined the effect of the SMF with only histomorphometric analysis. Therefore, further studies will be needed to examine precisely how the magnetic field of a neodymium magnet affects the bone tissue. In addition, many different types of experiments on magnetic fields will be needed to reach a better understanding of the effect of SMF on bone formation.

**Abbreviations**

BIC: bone-to-implant contact
BV: bone volume
ICNIRP: International Commission on Non-ionizing Radiation Protection
PEMF: pulsed electromagnetic field
SLA: sandblasted, large-grit, acid-etched
SMF: static magnetic field

**References**

21. Xu S, Tomita N, Ohata R, Yan Q, Ikada Y. Static magnetic