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ORIGINAL ARTICLE

Effect of corrosive environments and thermocycling on the attractive force of four types of dental magnetic attachments

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Abstract *Background/purpose:* One of the problems that has limited magnets' wide acceptance by clinicians is their low corrosion resistance. The purpose of this study was to determine the effect of corrosive environments and thermocycling on the attractive force of different types of new generation magnetic attachments.
Materials and methods: We measured the attractive forces of 60 magnetic attachment systems (Hyper slim, Hicorex slim, Dyna, and Steco) with a universal test machine. We then immersed 40 of the magnetic attachment systems in two media, namely, 1% lactic acid solution (pH 2.3), and 0.9% NaCl solution (pH 7.3). The remaining magnetic attachments were put through 10,000 thermal cycles (5 °C/55 °C). We measured the attractive forces of the magnetic attachment systems again after immersion and thermocycling to compare data. The data were statistically evaluated with one-way analysis of variance, paired samples *t*-test, and *post hoc* Tukey—Kramer multiple comparison tests ($\alpha = 0.05$).
Results: We found significant differences between the mean values before and after immersion in corrosive environments ($P < 0.05$). In contrast to the Dyna and Steco systems ($P < 0.001$), the differences between the attractive forces before and after thermocycling were not statistically significant for the Hicorex slim and Hyper slim systems ($P > 0.05$).
Conclusion: Magnetic attachments showed lower attractive force after immersion in corrosive environments compared to their initial retentive force. In addition, closed-field systems were not affected by the thermocycling procedures and were more resistant than open-field systems to thermal variations characteristic of the oral cavity.

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Introduction

Over the past century, dental magnetic attachment systems have been used in prosthodontics[1–5] and orthodontics[6–8] to retain dentures, for overdenture retention,[2,8–11] and for multicomponent maxillofacial prostheses.[12] Magnetic attachments have several advantages, such as ease of cleaning, retention that is not reduced with use, ease of placement for both dentist and patient, automatic reseating,[5] and less horizontal stress transmission.[11]

The first recorded use of magnets in dentistry can be dated to 1941, when Freedman used curved magnets to improve the stability of dentures for grossly resorbed mandibular alveolar ridges.[13] Then in 1950, Behrman surgically implanted magnets in the mandible of an edentulous patient.[5,13] These first attempts used aluminum—nickel—cobalt (Al—Ni—Co) magnets. In 1952, the introduction of smaller and stronger cobalt—platinum (Co—Pt) magnets allowed continuation of clinical trials.[14] These early magnetic systems were unsuccessful mainly due to the large size of the magnets required to provide adequate retentive force and their lack of corrosion resistance in the oral environment. Significant advances have been made in the development of hard magnetic substances, and these advances have been quickly transferred into dental applications. The introduction of rare earth magnets such as neodymium—iron—boron (Nd—Fe—B) and samarium—cobalt (Sm—Co) has resulted in magnets with small enough dimensions to be used in dental applications that still provide sufficient force.[15] Since the advent of these small rare earth magnets, dental applications using magnets have increased.

Both neodymium—iron—boron and samarium—cobalt are extremely brittle and susceptible to corrosion, especially in chloride-containing environments such as saliva.[5,16] Preventing corrosion of magnets is the main problem that limits their long-term clinical use. One approach is encapsulation in stainless steel or titanium within the oral environment.[5,8] Corrosion occurs by breakdown of the encapsulating material or diffusion of moisture and ions through the epoxy seal.[16] Nowadays, a highly reliable technique, laser welding sealing, is in use on the new generation of magnetic attachment systems. In this technique, a shield ring made of stainless steel (SUS447J1 or SUS316L) or titanium is welded in the boundary between the cup and disk yokes using a laser beam.[17] On the other hand, a variety of magnetic systems including open- and closed-field are available. Attachment of closed-field magnets is more efficient because both the north and south poles are used to attract the keeper, and the keeper can contain magnetic flux, whereas only one pole is used in open-field systems.

In the oral cavity, materials are usually subject to thermal variation. Such thermal variation may cause fatigue fractures in the material during long-term clinical use.[18] Therefore, magnetic attachments must have high resistance to the thermal variation of the oral cavity. Thermocycling has been proposed as an efficient method to provide *in vitro* simulation of *in vivo* conditions. Thermocycling simulates the introduction of hot and cold extremes in the oral cavity that occur through eating, drinking, and breathing, thus simulating the natural aging process of dental restorations.[19] The ISO TR 11450 standard indicates that a thermocycling regimen of 500 cycles in water between 5 °C and 55 °C is an appropriate artificial aging test.[20] A recent literature review concluded that 10,000 cycles corresponds approximately to 1 year of *in vivo* exposure.[21]

The purpose of this study was to examine both the effect of two different pH corrosive environments and the effect of thermocycling on the attractive force of different types of new generation magnetic attachments. The null hypotheses were: (1) there is significant difference in attractive force of magnets after immersion in corrosive environments; and (2) attractive forces of magnets are not affected by thermocycling procedures.

Materials and methods

We selected four types of magnetic attachment systems for this study: Hyper slim 5513 (Hitachi Metals; Tokyo, Japan), Hicorex slim 3513 (Hitachi Metals), Dyna 500gr (Dyna Dental Engineering; Bergen, Holland), and Steco-Teleskop Titan-magnetics (Steco-system-technic; Hamburg, Germany) (Table 1). We prepared 120 acrylic resin blocks with dimensions of 20 × 20 × 20 mm using autopolymerizing acrylic resin (Vertex Orthoplast; Vertex-Dental B.V., Zeist, Holland). Magnetic attachments were embedded in the center of the acrylic resin blocks. Then, we fixed the specimens to the jigs of the testing machine with an adhesive resin (Super Bond; Sun Medical Co., Shiga, Japan). We measured the attractive forces of the attachment systems using a universal testing machine (Lloyd LF Plus; Ametek Inc. Lloyd Instruments, Leicester, United Kingdom) at a head speed of 50 mm/min. For each attachment system, we measured the attractive force by attaching the specimen to five different magnets measurements, repeating this procedure 10 times, and then averaging the data.

After the measurement of the attractive forces, the magnets were immersed in two corrosive media. We immersed five of each type of specimens individually in each plastic plate (Fıratmed; Fıratmed, Istanbul, Turkey)

Table 1 General properties of magnetic attachments.

	Magnetic field	Rare earth magnet	Use
Hyper slim	Closed-field	Nd—Fe—B	Sectional denture and obturator
Hicorex slim	Closed-field	Nd—Fe—B	Sectional denture and obturator
Dyna	Open-field	Nd—Fe—B	Root and implant
Steco	Open-field	Sm—Co	Root and implant

with 10 mL of 1% lactic acid solution (pH 2.3) and 10 mL of 0.9% NaCl solution (pH 7.3). Plastic plates were placed in a 37 °C water bath (BM 302; Nüve, Ankara, Turkey) for 14 days. After 14 days of immersion, we removed the magnets from their respective corrosive media, then rinsed, dried, and cleaned them before measuring the attractive force. Next, we measured the attractive forces of the magnets with a universal testing machine as previously described and recorded the data.

We then conducted thermocycling for the remaining specimens in a thermocycling machine (Nova; Nova Ticaret, Konya, Turkey). Each cycle consisted of water baths of 5 °C and 55 °C, with a dwelling time of 30 seconds and a transfer time of 7 seconds. We administered 1000 thermocycles per week, totaling 4000 thermocycles at the end of 1 month and 10,000 thermocycles after a 2.5-month period. Next, we removed specimens from the thermocycling machine and measured the attractive forces after thermocycling. We then calculated the mean value and standard deviation of the specimens for each system using one-way ANOVA, paired samples *t*-test, and *post hoc* Tukey—Kramer multiple comparisons tests ($\alpha = 0.05$).

Results

One-way ANOVA test results of attractive force measurements are summarized in Table 2. The strongest attractive force was found in the Hyper slim system. In addition, the closed-field systems demonstrated greater attractive force than the open-field systems ($P < 0.001$). When attractive forces of magnets before immersion were compared with their attractive force after immersion, there was a significant difference ($P < 0.001$). All magnets showed lower attractive force after immersion in corrosive environments. The differences between the attractive forces obtained in lactic acid and NaCl solutions were not significant for the Dyna, Steco, and Hyper slim magnetic attachment systems.

In contrast to the Dyna and Steco systems ($P < 0.001$), the differences between the attractive forces before and after thermocycling were not significant for the Hicorex slim and Hyper slim systems ($P = 0.674$ and $P = 0.999$). It was found that closed-field systems were not affected by the thermocycling procedure and are thus more resistant than open-field systems to thermal variation of the oral cavity.

Discussion

The results obtained in this study clearly demonstrate that corrosive environments affect the attractive forces of magnets, indicating that the first hypothesis should be accepted. The second hypothesis was partially rejected, since—contrary to results from closed-field systems—open-field systems were affected by the thermocycling procedure.

It is well established that magnet cores sealed with excellent corrosion-resistant materials using laser welding do not corrode, and that they release no ions at all. Okuno and Takada[22] reported that laser welding was stable in terms of corrosion, because the weld zone did not break down at a lower potential in the anodic polarization curves of the magnetic attachments. Nevertheless, Boeckler et al[23] reported that neodymium and boron ions were released into the corrosive environment. Similar to Boeckler et al,[23] Akin et al[17] reported that there was significant decrease in the corrosion of the magnets, but corrosion was not completely stopped, because the laser welding zone began to break down and corrosion reached the magnet. The results of the present study are in accordance with those of Boeckler et al[23] and Akin et al.[17] Similarly, Yiu et al[13] found that NdFeB magnets exhibited significantly lower attractive force in 1% lactic acid solution.

Fluids in the intraoral environment include dental plaque, which consists of proteins and organic acids, such as lactic, formic, and inorganic acids. As for pH, human saliva is reported to have a pH of 6.2 to 7.6 in static conditions. The pH increases to approximately 4 when sucrose is consumed, and the pH of foods and beverages can range from 2.0 to 11. In recent studies, researchers used lactic acid solution[4,13,24–26] and NaCl solution[4,26,27] for corrosive media. On the other hand, the literature shows prior studies have used many different experimental immersion periods. Noar et al[28] used grinding media to evaluate corrosion performance of the magnets over a 1- to 7-hour immersion period. Assis et al[29] investigated the *in vitro* corrosion resistance of superferritic stainless steel in naturally aerated Hank's solution for 72 hours. In addition, Ahmad et al[8] evaluated the corrosion resistance of rare earth magnets in artificial saliva over 4 weeks. They also immersed magnets in lactic acid solution for 2, 24, 48, and 168 hours to evaluate corrosion performance of the magnets. Moreover, Hai et al[24] and Endo et al[27] used a 7-day immersion period, whereas Yiu et al[13] investigated corrosion of magnets after 28 and 60 days. Kitsugi et al[26] evaluated the corrosion resistance of magnets over a 42-day immersion period. Furthermore, Akin et al[17] immersed magnets for 14 days to determine the corrosion performance of laser-welded new-generation magnets. Following this approach, the present study used an immersion period of 14 days.

The maximum retention force of a magnetic attachment is the force required to cause initial separation of the

Table 2 Mean attractive force and SD of magnetic attachment systems.

Magnetic attachments	Manufacturer's purported value	Mean value	Mean value after lactic acid	Mean value after NaCl	Mean value after thermocycling
Dyna	5.1[a]	4.19 (0.19)[b]	3.09 (0.33)[c]	2.84 (0.48)[c]	3.09 (0.38)[c]
Hicorex slim	4.8[d]	4.01 (0.28)[e]	3.47 (0.43)[f]	2.57 (0.39)[g]	3.85 (0.52)[e]
Hyper slim	12.2[h]	9.28 (0.73)[i]	7.05 (1.04)[j]	7.38 (0.96)[j]	9.22 (0.52)[i]
Steco	3[k]	2.3 (0.22)[l]	1.5 (0.22)[m]	1.37 (0.23)[m]	1.99 (0.26)[n]

[a-n] For each horizontal row, values with same superscripted letters indicate no statistically significant difference ($P > 0.05$).

magnet from its opposing attractive element. The breakaway force of magnetic attachments also depends on the speed of separation of the two components. As a result, there are no generally valid instructions or ISO norms available for fixing the characteristic force—attraction curves of magnetic attachments. Yiu et al[13] used an instron testing machine with the crosshead speed set at 2 mm/min to determine the attractive force. However, Watanabe et al[1] used a 5 mm/min crosshead speed. On the other hand, Akaltan and Can,[10] Akin et al,[14] and also Chung et al[11] used 50 mm/min crosshead speed to determine the attractive force of the magnetic attachment systems. They emphasized that the faster speed (50 mm/min) more closely simulates the speed of the mandible as it draws away from the denture base during mastication.[3,10] Therefore, we selected a 50 mm/min crosshead speed for our study.

Magnetic alloys are sensitive to temperature increases.[30] The maximum temperature (T_{max}) for SmCo is approximately 220—350 °C. NeFeB is more sensitive to temperature, and its T_{max} is approximately 100—200 °C. Heating beyond these temperatures can lead to a reversible decrease in magnetic forces. On cooling, the magnetic force should be reestablished. Higher temperatures, however, can result in irreversible demagnetization. Boeckler et al[31] found that autoclave sterilization caused a nonsignificant reduction of 0.04—14.6% in retentive force when compared with the unsterilized magnet pairs (10 minutes at 134 °C). On the other hand, intraoral temperature does not reach 134 °C. Thermocycling is a widely used artificial aging methodology. The use of thermocycling of dental restorations is frequently used in laboratory studies in order to simulate changing intraoral temperature conditions. A recent literature review concluded that 10,000 cycles corresponds approximately to 1 year of *in vivo* functioning.[21] This study showed that open-field systems were not resistant to thermal variations typical of the oral cavity. There are three possible causes of the loss of attractive force in open-field systems. First, production processes, which include casting and thermal processes, may vary. Second, composition of the attachments or the proportion of metals composing attachments could vary. Finally, magnetic systems (open-field) could be effective for this result.

Within the limitations of this study, after immersion in corrosive environments, magnetic attachments showed lower attractive force than they did initially. Furthermore, thermal cycling caused a significant reduction of 13—26% in retentive force in open-field magnetic attachments, when compared with their initial retentive force. Nd—Fe—B and closed-field magnets such as Hyper slim magnets could be a promising new candidate for prosthetic application.

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