

RESEARCH

Radiofrequency heating and magnetically induced displacement of dental magnetic attachments during 3.0 T MRI

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Objective: The aim of this study was to estimate the risk of injury from dental magnetic attachments due to their radiofrequency (RF) heating and magnetically induced displacement during 3.0 T MRI.

Methods: To examine the magnetic attachments, we adopted the American Society for Testing and Materials F2182-02a and F2052-06 standards in two MRI systems (Achieva 3.0 T Nova Dual; Philips, Tokyo, Japan, and Signa HDxt 3.0 T; GE Healthcare, Milwaukee, WI). The temperature change was measured in a cylindrical keeper (GIGAUSS D600; GC, Tokyo, Japan) with coping of the casting alloy and a keeper with a dental implant at the maximum specific absorption rate (SAR) for 20 min. To measure the magnetically induced displacement force, three sizes of keepers (GIGAUSS D400, D600 and D1000) were used in deflection angle tests conducted at the point of the maximum magnetic field strength.

Results: Temperature elevations of both coping and implant were higher in the Signa system than in the Achieva system. The highest temperature changes in the keeper with implant and keeper with coping were 0.6 °C and 0.8 °C in the Signa system, respectively. The temperature increase did not exceed 1.0 °C at any location. The deflection angle (α) was not measurable because it exceeded 90°. GIGAUSS D400 required an extra 3.0 g load to constrain the deflection angle to less than 45°; GIGAUSS D600 and D1000 required 5.0 and 9.0 g loads, respectively.

Conclusions: Dental magnetic attachments pose no risk due to RF heating and magnetically induced displacement at 3.0 T MRI. However, it is necessary to confirm that these keepers are securely attached to the prosthesis before imaging.

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Introduction

Dental magnetic attachments with satisfactory retentive force and stability are now commercially available for dental treatment. Such attachments are excellent retainers for removable partial dentures because they reduce trauma to the supporting roots by dissipating the lateral stress component on the abutment teeth, improve prosthesis retention and maintain a semipermanent retentive force. They are useful not only in

prosthodontics but also in maxillofacial prosthetics.^{1–3} Most commercially available magnetic attachments consist of two components: a keeper, which is generally made of stainless steel, and its corresponding magnetic assembly, which comprises a magnet and yoke made from ferromagnetic material. The magnetic assembly grips the keeper with a retentive force. The conventional fabrication method for dentures with magnetic attachments involves embedding the magnetic assembly in the denture base and inserting its corresponding keeper into the abutment root. This attachment is designed so that the magnet in the denture base can be removed before MRI, eliminating the possibility of demagnetization of the magnetic attachment after MRI. Consequently, a serious problem associated with

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magnetically attached dentures is the presence of irremovable ferromagnetic material in the oral area.⁴⁻⁸

MRI is a computer-based imaging technique that displays the body in thin tomographic slices. Recently, 3.0 T MRI scanners have started playing an important role in medical diagnosis. A clear advantage of 3.0 T MRI is the increased signal-to-noise ratio that scales linearly with the magnetic field strength (B_0).⁹ However, although radiofrequency (RF) heating of patients wearing medical metallic implants during MRI has always been a safety concern, it has recently received greater attention because of the increased application of interventional MRI and frequent use of a large number of RF pulses to achieve short scan times.^{5,10-17} The energy deposited in the patient's tissues is fourfold higher at 3 T than at 1.5 T. One index for measuring the dose of RF exposure is the specific absorption rate (SAR), which is defined as the absorbed electric power from RF irradiation per unit mass of the human body (measured in watts per kilogram). The SAR is the current standard for characterizing the thermogenic aspects of this electromagnetic field.¹⁸ Another concern is the physical safety of patients with metallic implants during MRI. The development of a sufficient ferromagnetic field can cause migration of metallic devices and consequent tissue damage. The degree of force experienced by a metallic device is proportional to the main magnetic field and the field strength gradient.¹⁸

The safety of MRI has been studied for many different types of bioimplants.^{11,14,17,19} However, despite the close proximity of the oral area to the brain and chest, few reports on the safety of MRI are available for patients with magnetically attached dentures. The absence of data on the safe use of MRI in patients with ferromagnetic material orally is a particular concern for health workers who use such procedures.^{10,13} The American Society for Testing and Materials (ASTM) requires determining whether the presence of a passive implant could cause injury to the individual with the implant during an MRI procedure. The test method covers measurement of the magnetically induced displacement force on a medical device and RF heat near a passive implant during MRI.¹⁹⁻²² In this study, our goal was to estimate the risk of injury from dental magnetic attachments due to their RF heating and magnetically induced displacement during 3.0 T MRI according to the ASTM standards.

Materials and methods

Assessment of heating

Experimental procedure: We measured the 3.0 T MRI-related RF heating in three phantom conditions (phantom without prosthesis as a control, phantom with a dental implant and keeper, and phantom with a coping and keeper) by using two MRI systems (Achieva 3.0 T Nova Dual; Philips, Tokyo, Japan, and Signa HDxt 3.0 T; GE Healthcare, Milwaukee, WI). This test was conducted

using the ASTM F2182-02a standardized procedure for RF-induced heating near passive implants.¹⁹ In these measurements, the centre of the prosthesis coincided with the centre of the static magnetic field.

Maximum RF heating was achieved using the maximum possible SAR parameters during 20 min RF irradiation (Table 1). The console-predicted, whole body-averaged SAR was about 0.9 W kg^{-1} in the Achieva 3.0 T Nova Dual system and 3.0 W kg^{-1} in the Signa HDxt 3.0 T system in the normal operating mode.

Clinical simulation: To simulate RF heating clinically, we used two common types of dental prosthesis serving as abutments for magnetically attached dentures. GIGAUSS D600 keepers (GC, Tokyo, Japan; 0.058 g; UNS S44627) were used. One prosthesis comprised the keeper and a coping made of casting alloy (Pallatop 12 Multi; Dentsply-Sankin, Tokyo, Japan; 0.941 g); the unit had a gross weight of 0.999 g and a length of 10 mm. A dental model (X-465; Nissin Dental Products, Inc., Kyoto, Japan) with artificial teeth (A50AN-118; Nissin Dental Products, Inc.) was used for making this prosthesis. The other prosthesis comprised a keeper and a dental implant (SETio FIXTURE, 10 mm, $\phi 3.8$ mm, and custom abutment; GC; 0.663 g) made of Ti; this unit had a gross weight of 0.721 g and a length of 14 mm. The keeper was cemented (Fuji Luting Cement, GC) to the coping or implant (Table 2, Figure 1).

A tissue-equivalent phantom was prepared. The phantom consisted of dissolved powdery gelatinizer with 10.0 wt% carrageenan (Cool Agar; Nitta Gelatin, Inc., Osaka, Japan) in distilled water with 0.9 wt% NaCl (table salt) to adjust the electrical properties equivalent to those of soft tissue. We used an acrylic resin container of 20 cm length and 20 cm width to fill the prepared semisolid gel to a depth of 10 cm. The resulting phantom weighed 4 kg. Each coping and dental implant was embedded perpendicular to the direction of the static magnetic field in the phantom.

Table 1 Operational modes for the radiofrequency heating tests

MRI system	Achieva 3.0 T Nova Dual ^a	Signa HDxt 3.0 T ^b
Coil	Body-coil	Body-coil
Pulse sequence	T-SE	T-SE
Time (min)	20.02	20.19
TR (ms)	586	2340
TE (ms)	15	8.104
ETL	4	126
Flip angle	90°	90°
Number of slices	5	5
Slice thickness (mm)	10	5
Band width (Hz)	2003.2	166.67
FOV (mm)	200	200
NSA	19	51
Body-averaged SAR (W kg^{-1})	0.9	3.0

ETL, echo train length; FOV, field of view; NSA, number of sample (signals) averaged; SAR, specific absorption rate; TE, echo time; TR, repetition time.

^aManufactured by Philips, Tokyo, Japan.

^bManufactured by GE Healthcare, Milwaukee, WI.

Table 2 Materials evaluated in the radiofrequency heating tests

Material	Trade name	Composition	Dimension (mm)	Weight (g)
Keeper	GIGAUSS D400 ^a	UNS S44627	φ3.0 × 0.6	0.034
	GIGAUSS D600 ^a	UNS S44627	φ3.6 × 0.7	0.058
	GIGAUSS D1000 ^a	UNS S44627	φ4.9 × 0.8	0.119
Dental implant	SETio FIXTURE 10 mm (φ3.8) custom abutment ^a	Ti		0.663
Casting alloy	Pallatop 12 Multi ^b	12% Au, 20% Pd, 50% Ag, 15% Cu		0.941

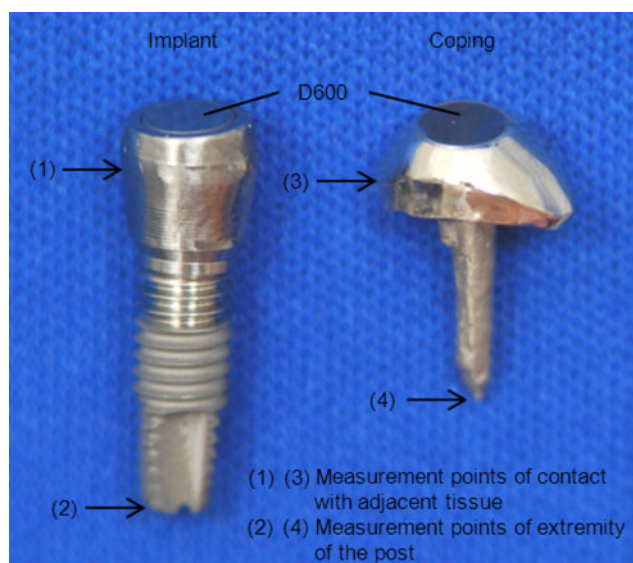
UNS, unified numbering system.

^aManufactured by GC, Tokyo, Japan.

^bManufactured by Dentsply-Sankin, Tokyo, Japan.

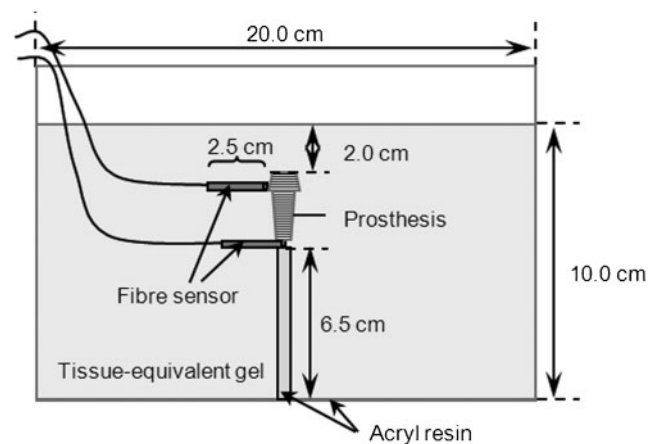
Each prosthesis was positioned at a depth of 20 mm from the phantom's surface because of the skin effect of RF energy transfer (Figure 2).

Temperature measurement: We measured temperature by using two fibre-optic thermometers (FL-2000; Anritsu Meter Co., Tokyo, Japan). The thermometers' optical fibres (Fs100-5M, Anritsu Meter Co.) were 5 m in length and unaffected by magnetic forces or RF irradiation. This device has an accuracy and resolution of 0.1 °C. The temperature was measured by placing the sensors in close contact with the surface of the prosthesis, and the difference in temperature before and after RF irradiation was recorded as the experimental temperature increase. Measurement positions on the prostheses are shown in Figure 1. To examine the effects of temperature on the marginal gingival tissue and abutment root or alveolar bone, the measurement positions were set at points of contact with adjacent tissue (Points 1 and 3) and at the extremity of the post (Points 2 and 4). Temperature was recorded at intervals of 1 s from 2 min before to 2 min after RF irradiation. The room temperature was set in advance to 23 °C, and the phantom was placed in the room at least 12 h before the measurements.

**Figure 1** Dental prostheses and measurement points

Assessment of magnetic field

Deflection angle measurement: Cylindrical keepers (GIGAUSS D400, 600 and 1000) were evaluated for the magnetically induced displacement force (Table 2). In this test, each dental prosthesis was suspended from a polyester thread (length 15.0 cm; weight 0.2 mg), and the thread was attached to a sturdy plastic protractor such that the angle of deflection from the vertical (α) could be measured (Figure 3a). The error of this measuring device was $\pm 0.5^\circ$ based on the ability to read the protractor within the MRI system. The deflection angle test was conducted at the point in the 3.0 T MRI system where the spatial gradient of the magnetic field was determined in preliminary studies to have maximum strength (Figure 3b). In our previous study, no difference in the deflection angle between the Achieva 3.0 T Nova Dual and the Signa HDxt 3.0 T systems was found; therefore, the measurements were conducted in the Achieva 3.0 T Nova Dual system. The highest spatial gradient in the Achieva 3.0 T Nova Dual system was 83.0 cm. Deflection angles were measured three times, and the magnetically induced deflection force on the dental prosthesis was calculated from the mean value of the observed deflection angle according to the following formula: $Fm = mg \tan \alpha$, where m is the mass of the device and g is the acceleration due to gravity. The range of α in which Fm has a positive value is $-90^\circ < \alpha < 90^\circ$; therefore, the measurements were constrained within 90° by adding an additional load to

**Figure 2** Gel phantom and fibre sensors

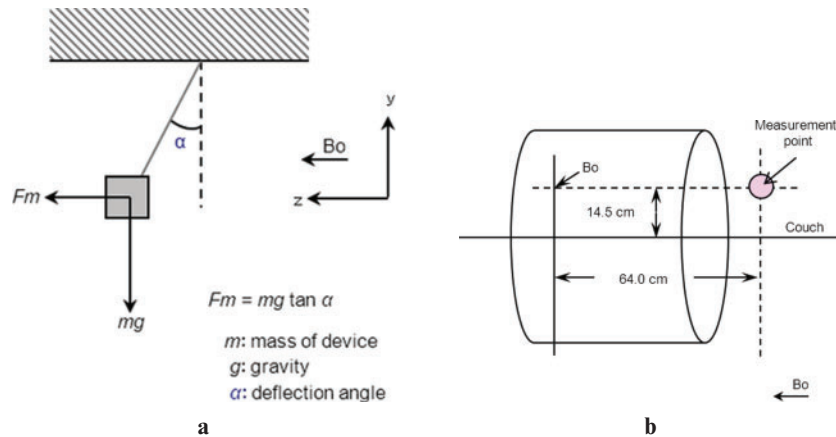


Figure 3 (a) Deflection angle α ; (b) measurement point observed at the highest spatial gradient point, 86.0 cm from the centre of the magnetic field and 14.5 cm from the couch

the device. The load was applied by adding weights composed of non-magnetic material. When the deflection angle was greater than 45° , the load was measured to determine the weight required to constrain the deflection angle of the keeper within 45° .

Results

Radiofrequency heating

All temperatures increased gradually during RF irradiation. The gel temperature increased by 0.3°C in the Achieva 3.0 T Nova Dual system and 0.4°C in the Signa HDxt 3.0 T system during 20 min RF irradiation. The temperature elevations of both the coping and the implant at measurement Points 1 and 3 (adjacent tissue) were larger than those at Points 2 and 4 (the extremity of the post). The mean value of temperature elevation in 1 min and the standard error of the mean are indicated in Figure 4.

In the assessment of RF heating associated with the coping, the highest temperature increase was approximately 0.6°C with the Achieva 3.0 T Nova Dual system, and 0.8°C with the Signa HDxt 3.0 T system. The highest temperature increase for the implant was approximately 0.4°C with the Achieva 3.0 T Nova Dual system, and 0.6°C with the Signa HDxt 3.0 T system (Figure 4). However, the temperature increase did not exceed 1.0°C at any location.

Displacement force

The deflection angle of the keeper exposed to the 3.0 T MRI system was not measurable because it exceeded 90° . The deflection angles observed with various added loads are shown in Figure 5a. The GIGAUSS D400 keeper required an additional load of 3.0 g to constrain the deflection angle within 45° , and the GIGAUSS D600 and D1000 keepers required loads of 5.0 and 9.0 g, respectively. The magnetically induced deflection force ($1 \text{ dyn} = 10^{-5} \text{ N}$), which was calculated for the keepers by using the mean value of the deflection angle with added loads, is presented in Figure 5b.

Discussion

The increasing use of dental magnetic attachments and growing popularity of MRI suggest that more patients with magnetically attached dentures will undergo MRI scans. The major concerns in this regard are the health risks associated with RF heating and magnetically induced displacement of dental magnetic attachments. In this study, we evaluated these potential hazards to determine the MRI compatibility of dental magnetic attachments.

The SAR is routinely used for reporting the safety of clinical MRI procedures in the presence of conductive implants.¹⁹ However, this may not be appropriate because the SAR is primarily an index of heating in biological tissue devoid of metallic or conductive implants. Furthermore, the methods for SAR calculation across MRI systems are different.^{23–25} Baker *et al*²³ reported that the amount of heating per unit change in the calculated whole body-averaged SAR, as recorded at an implantable metal implant, was profoundly different between two different generation 1.5 T MR systems from the same manufacturer. Therefore, the use of the SAR indicated by an MRI system console for establishing implant-related safety may be dangerous. The possibility of RF heating is higher at 3.0 T than that at 1.5 T, and the temperature elevation of a metal implanted device is expected to be different between every generation of 3.0 T MR systems. To evaluate the safety of magnetic attachment during the MR procedure, one 3.0 T MR system is probably not enough. Safety testing should be performed for every new implant used in current and future MRI systems.²⁵ In this study, we evaluated RF heating between two different shared general MR systems, Achieva 3.0 T Nova Dual and Signa HDxt 3.0 T.

Although we used the maximum SAR of the MRI systems in this study, the temperature increase upon RF irradiation was small at all locations. In the assessment of RF heating associated with the Achieva 3.0 T Nova Dual system, which has a maximum displayed SAR of

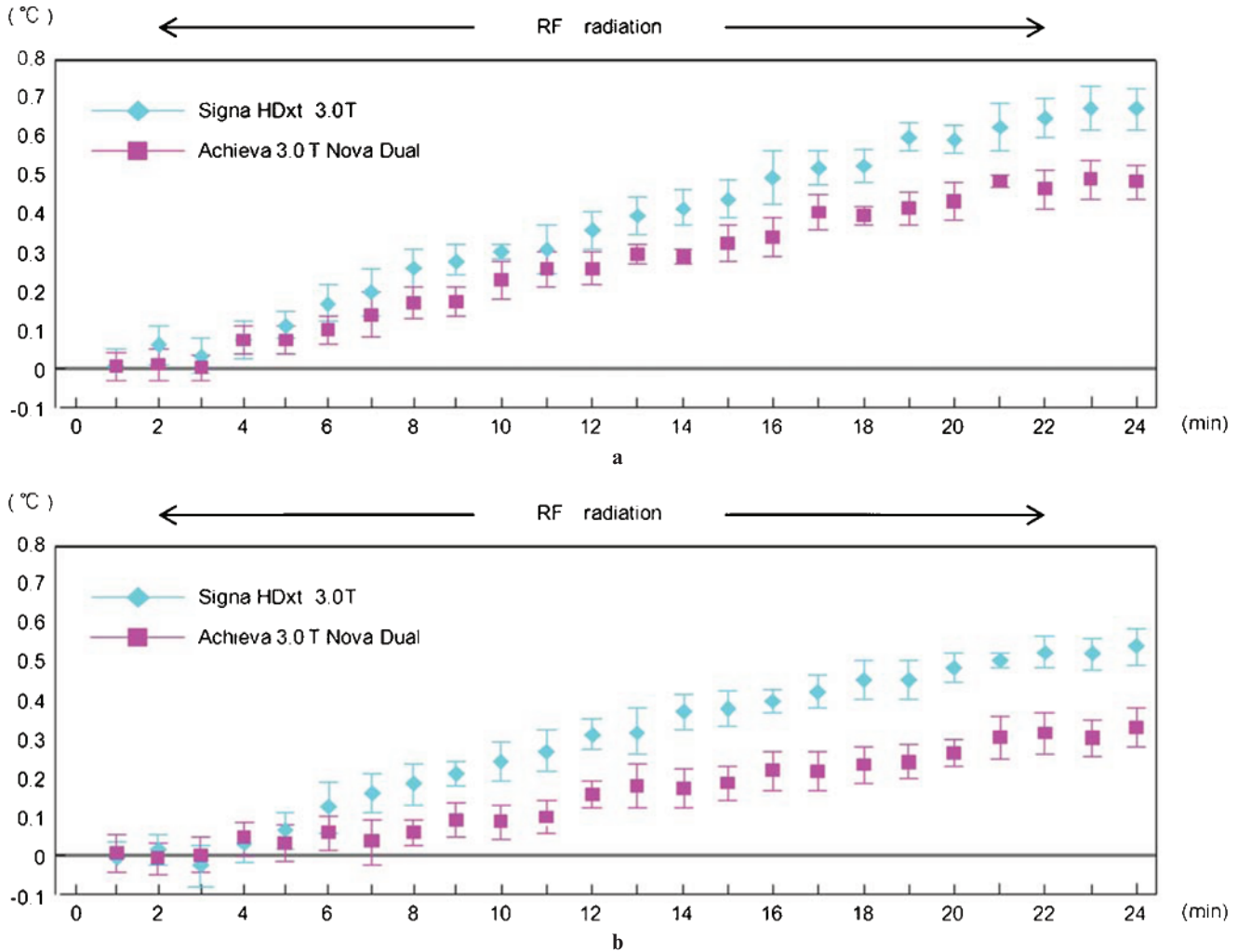


Figure 4 The mean values of temperature elevations per minute during radiofrequency irradiation in the Achieva 3.0 T Nova Dual system (Philips, Tokyo, Japan) and Signa HDxt 3.0 T system (GE Healthcare, Milwaukee, WI). (a) Temperature changes of the keeper with a metal coping in the Achieva 3.0 T Nova Dual system and Signa HDxt 3.0 T system. (b) Temperature changes of the keeper with a dental implant in the Achieva 3.0 T Nova Dual system and Signa HDxt 3.0 T system. RF, radiofrequency

0.9 W kg^{-1} , the highest temperature increase was approximately 0.4°C for the implant and 0.5°C for the coping. In the case of the Signa HDxt 3.0 T system, which has a maximum displayed SAR of 3.0 W kg^{-1} , the highest temperature increase was approximately 0.6°C for the implant and 0.8°C for the coping. Temperature elevations were higher in the Signa HDxt 3.0 T system than in the Achieva 3.0 T Nova Dual system. This result indicated the amount of RF power absorbed by the coping or implant was higher in the Signa HDxt 3.0 T system than in the Achieva 3.0 T Nova Dual system; however, the degree of temperature elevation was not proportional to the indicated SAR by the MRI system console; therefore the console-reported SAR does not exactly constitute a reliable index of heating for implants.

A keeper with coping is set in an abutment root, and a keeper with implant is installed in alveolar bone. The possible consequences of thermal variations in abutment roots include damage to the cemental layer, resorption of

roots and periodontal ligament fibres, alveolar bone necrosis and pain.^{26–28} Eriksson *et al*²⁹ reported that temperatures above $56\text{--}60^\circ\text{C}$ can cause protein denaturation in hard tissues. The thermal variations in alveolar bone also result in implant loss, necrosis and pain. According to Eriksson and Albrektsson,²⁶ exposure to temperatures of $44\text{--}47^\circ\text{C}$ ($7\text{--}10^\circ\text{C}$ above body temperature) for 1 min is sufficient to cause alveolar bone necrosis. Further, Ramsköld *et al*³⁰ reported that an increase in temperature could be deleterious to tissues adjacent to the tooth, although elevations of 10°C for 1 min are still considered safe for periodontal tissue, which is less susceptible to thermal damage than bone tissue because of its high degree of vascularization.^{30,31} The temperature increase in magnetic attachments is far below the safety limit of 10°C . Although this standard covers all medical implants, the increase in this study was below the industrial standard of a maximal temperature increase of 2.0°C (CENELEC standard prEN45502-2-3), set to limit tissue damage and patient discomfort.

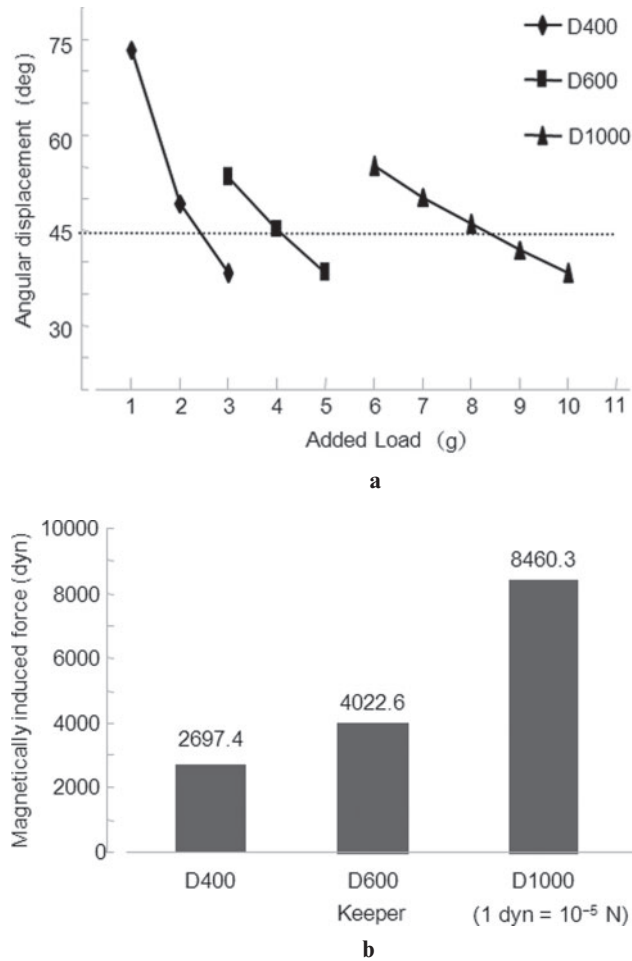


Figure 5 (a) Deflection angles observed with various added loads for the GIGAUSS D400, 600 and 1000 keepers. (b) Magnetically induced deflection force acting on the GIGAUSS D400, 600 and 1000 keepers (GC, Tokyo, Japan) (1 dyn = 10⁻⁵ N)

Another safety concern is the possible adverse effect of the displacement force acting on the prosthesis owing to the magnetic field. The deflection angle test is required to determine whether the presence of a medical device can cause injury to individuals during an MRI examination or in an MRI environment.^{18,21} Under the specified standard, the magnetically induced force should not pose a risk greater than that associated with normal daily activity in the earth's gravitational field. According to the ASTM standard, if the device deflects less than 45°, then the magnetically induced deflection force is less than the force on the device owing to gravity (*i.e.* its weight).²¹ In this study, the magnetically induced deflection force acting on the keepers was strong. The deflection angles measured for the keepers were over 90°. Each keeper required extra weight, ranging from 3.0 g to 9.0 g, to constrain the deflection angle to less than 45°. However, these keepers were cemented onto or cast to a dental prosthesis; therefore, the strength of the dental cement used for luting could be considered sufficiently strong.³²⁻³⁴

In conclusion, we have demonstrated the feasibility of evaluating RF heating of keepers with copings or dental implants during MRI examinations and the interaction between MRI system-generated magnetic fields and keepers. The relatively minor RF heating (temperature increase = 0.8°C) of keepers with coping in the Achieva 3.0 T Nova Dual and Signa HDxt 3.0 T systems in the normal operating mode does not pose a risk to patients. Further, although the magnetically induced force acting on the currently used keepers could result in angular displacements of over 45°, because of their small masses, these keepers are not expected to pose risks such as movement or dislodgement in MRI environments of 3.0 T or less if they are securely cemented to the dental prosthesis. However, it is necessary to confirm that keepers are securely attached to the dental prostheses before MRI.

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