Eur Radiol (2007) 17: 533–540
DOI 10.1007/s00330-006-0335-x

J. Kemper
A. N. Priest
D. Schulze
B. Kahl-Nieke
G. Adam
A. Klocke

Orthodontic springs and auxiliary appliances: assessment of magnetic field interactions associated with 1.5 T and 3 T magnetic resonance systems

Received: 5 January 2006
Revised: 12 April 2006
Accepted: 8 May 2006
Published online: 29 June 2006

J. Kemper (✉) · A. N. Priest · G. Adam
Clinic of Diagnostic and Interventional Radiology, University Medical Center of Hamburg-Eppendorf,
Martinistrasse 52,
20246 Hamburg, Germany
e-mail: jkemper@uke.uni-hamburg.de
Tel.: +49-40-428034029
Fax: +49-40-428033802

B. Kahl-Nieke · A. Klocke
Department of Orthodontics,
University Medical Center of Hamburg-Eppendorf,
Hamburg, Germany

D. Schulze
Department of Oral and Maxillofacial Surgery,
University Hospital of Freiburg,
Freiburg, Germany

Abstract The objective of this paper is to evaluate magnetic field interactions at 1.5 and 3 T for 20 orthodontic devices used for fixed orthodontic therapy. Twenty springs and auxiliary parts made from varying ferromagnetic alloys were tested for magnetic field interactions in the static magnetic field at 1.5 and 3 T. Magnetic translational force F_z (in millinewtons) was evaluated by determining the deflection angle β [American Society for Testing and Materials (ASTM standard test method)]. Magnetic-field-induced rotational force F_{rot} was qualitatively determined using a five-point scale. β was found to be >45° in 13(15) devices at 1.5(3) T and translational force F_z exceeded gravitational force F_g on the particular object [F_z 10.17–261.4 mN (10.72–566.4 mN) at 1.5(3) T]. F_z was found to be up to 24.1(47.5)-fold higher than F_g at 1.5(3) T. Corresponding to this, F_{rot} on the objects was shown to be high at both field strengths (≥ +3). Three objects (at 1.5 T) and one object (at 3 T) showed deflection angles <45°, but F_{rot} was found to be ≥ +3 at both field strengths. For the remaining objects, β was below 45° and torque measurements ranged from 0 to +2. Of 20 objects investigated for magnetic field interactions at 1.5(3) T, 13(15) were unsafe in magnetic resonance (MR), based on the ASTM criteria of F_z. The implications of these results for orthodontic patients undergoing MRI are discussed.

Keywords Orthodontic appliances · Magnetic resonance imaging (MRI) · MR safety

Introduction

Fixed orthodontic appliances are used to treat a variety of tooth and jaw irregularities and are important components in fixed orthodontic therapy. In addition to brackets and wires, these appliances consist of a number of auxiliary parts that generate the forces necessary to align the teeth and jaws. Different types of springs within one jaw and between the jaws are used. While certain parts (e.g. Herbst appliance, expansion screw) are soldered or welded to bands that are cemented on the teeth, other parts are attached to the existing appliance with pliers and are held in place by frictional forces. Some parts of the appliance (e.g. lip bumper) can be removed by the patient for brushing and eating.

The number of orthodontic patients treated with these parts who are referred for magnetic resonance imaging (MRI) has increased in recent years [1]. Within this special clientele the proportion of adult patients also shows a steady rise. The radiologist is confronted with the problem of risk estimation for those patients. Therefore, safety questions related to MR diagnostics on patients with fixed orthodontic appliances are asked more frequently in daily routine. To date, over 1,100 medical implants and objects have been tested for this specific aspect of MR safety, and this information is systematically listed online [2]. As with any ferromagnetic device, the presence of an orthodontic object in the patient's mouth represents a potentially hazardous situation due to magnetic field interactions in the MR environment. Recently, information on magnetic field interactions for orthodontic brackets and wires has been published [3, 4]: a number of stainless steel objects were affected by the MR magnetic field and were classified ‘not MR safe’. However, no information on the above-mentioned orthodontic auxiliary parts has been presented so far. Therefore, the purpose of this study was to evaluate magnetic field interactions at 1.5 T and 3 T for auxiliary parts of the fixed orthodontic appliances commonly used in modern orthodontic therapy.

Materials and methods

Orthodontic appliances

A total of 20 commonly used orthodontic auxiliary parts were evaluated and are listed in Table 1. Within this collection, a variety of different auxiliary orthodontic parts are represented. The majority of the objects contain stainless steel alloys.

MR systems

Magnetic field interactions were evaluated for the objects using 1.5 T (Magnetom Symphony; Siemens Medical Solutions, Erlangen, Germany) and 3 T (Intera, Philips Medical Systems, Best, Netherlands) MR systems.

Because of technical design differences in magnets used for MR systems, the findings for magnetic field interactions for the implants tested are specific to these scanners or to MR systems with comparable spatial gradients with respect to the measured displacement forces [5, 6].

Measurement of magnetically induced translational force F_z

Translational force F_z was assessed for each object using the standardized “deflection angle test” described by the American Society for Testing and Materials (ASTM) [7]. It was introduced by New et al. in 1983, and, in a modified version, it has become a standard for measurement of forces on ferromagnetic objects in the MRI environment [8–11].

The experimental setup is shown in Fig. 1. Each orthodontic auxiliary was attached to the distal end of a 30-cm-long lightweight thread at the approximate centre of mass of the object. The weight of the thread was less than 1% of the weight of the object for all orthodontic devices investigated. The proximal end of the thread was attached to a plastic protractor that allowed measurement of the deflection of the thread from a vertical line. The angle of deflection was measured to the nearest 0.5°. For objects exhibiting a deflection angle ≥65°, additional measurements were complemented with non-ferromagnetic weights made from non-ferromagnetic brass wire attached to the thread to improve the accuracy of the force measurements [8, 12]. Prior to the experiment it was confirmed that the non-ferromagnetic weights were not influenced by attractive forces due to the magnetic field and, thus, did not cause any deflection of the thread. Measurements of the deflection angle were repeated three times and averaged. Pearson correlation coefficient r was calculated for the translational force F_z at 1.5 T and 3 T.

Translational force F_z was calculated from the following formula:

$$F_z = m \cdot g \cdot \tan\ \beta$$

$$\left[\begin{array}{l} F_z = \mathit{translational\ force}; \\ m = \mathit{device\ mass}; \\ g = \mathit{gravity}\ \left(9.81\ m/\mathrm{sec}^2\right); \\ \beta = \mathit{measured\ angle\ of\ deflection} \end{array}\right]$$

We converted the deflection angle values (β) to displacement force ratios (F_z/F_g) by dividing the attractive force due to the magnetic field F_z by the force of attraction due to gravity (F_g). If the object was deflected less than 45° (i.e. $F_z/F_g<1.0$), then the magnetically induced translational force was less than the force on the object due to gravity, a prerequisite to be defined as “MR safe” by the ASTM standard [7].

The test was performed at the position where the spatial gradient of the magnetic field was considered to be at a maximum: the position for testing was previously determined and calibrated with a stainless steel weight and a non-ferromagnetic weight and was found to be 37 in. (94 cm) from the isocentre of the magnet at 1.5 T and 38.6 in. (98 cm) at 3 T [12]. Height and distance from the isocentre were marked to allow reproducible measurement of the deflection force on the objects.

Measurement of magnetically induced rotational force F_{rot}(torque)

The assessment of magnetic field interactions was conducted to determine the presence of magnetic field-induced rotational force F_{rot} (i.e. torque) for the orthodontic objects. Because of the inherent difficulty of determining rotational forces on very small objects, we could not apply the ASTM standard test method for the measurement of magnetically induced torque, which is based on the use of a torsional spring [13]. F_{rot} was qualitatively assessed using a modification of the method originally described by Nogueira and Shellock for the assessment of torque of small implants. Each object was placed on a plastic-coated platform with a millimetre grid etched on the bottom (Fig. 2) [14, 15]. We obtained measurements by placing the test apparatus with the object in the isocentre of the MR scanners, where the

Table 1 Auxiliary orthodontic appliances at 1.5 T and 3 T

Name/ specification/ order number	Device	Manufacturer	Weight (g)	Deflection angle β [°]		Corrected angle β [°]*		Gravity F_g [mN]	Translational force F_z		Ratio F_g/F_z		Torque F_{rot}	
				1.5 T	3 T	1.5 T	3 T		1.5 T	3 T	1.5 T	3 T	1.5	3T
Memory Titanol Spring 0.017×0.025″/307-1010	Intramaxillary spring	Forestadent, Pforzheim, Germany	0.158	90.00	90.00	47.30	31.67	1.55	11.15	22.13	7.20	14.30	4	4
NiTi, closed coil medium/10-000-02		GAC, Central Islip, N.Y., USA	0.039	2.00	9.17			0.38	0.01	0.06	0.03	0.16	1	2
Sentalloy open coil spring medium/10-000-08		GAC, Central Islip, N.Y., USA	0.015	0.00	0.00			0.15	0.00	0.00	0.00	0.00	0	0
Hi-T II coil spring close wound 0.010″ stainless steel/341-530		3M-Unitek, Monrovia, Calif., USA	0.272	90.00	90.00	58.00	51.00	2.67	59.19	117.00	22.20	43.90	4	4
Hi-T II coil spring open-space wound 0.010″ stainless steel/341-531		3M-Unitek, Monrovia, Calif., USA	0.043	90.00	90.00	48.00	30.00	0.42	10.17	20.06	24.09	47.50	4	4
Herbst I, telescope (max.) and screw/607-100-00	Herbst appliance	Dentaurum, Ispringen, Germany	1.168	26.50	47.67			11.46	5.72	12.58	0.50	1.10	3	4
Jasper Jumper UR7/852-907R	Intermaxillary spring	American Orthodontics, Sheboygan; Wis., USA	1.338	71.17	90.00	51.00	47.00	13.13	58.59	112.82	4.46	8.60	4	4
Sabbagh Universal Spring/607-130-00		Dentaurum, Ispringen, Germany	1.524	90.00	90.00	44.00	41.00	14.95	47.58	93.04	3.20	6.20	4	4
Eureka spring closed 23 mm		Eureka Spring, San Louis Obispo, Calif., USA	0.826	63.33	90.00		38.83	8.10	16.21	34.14	2.00	4.21	4	4
Flex Developer "FD" variable length		LPI-Ormco, Maria Anzbach, Austria	1.067	20.00	45.67			10.47	3.81	10.72	0.36	1.02	3	3
Bite Fixer/L4/600-2004		Ormco, Orange, Calif., USA	1.190	78.83	90.00	36.00	54.00	11.67	75.38	142.80	6.50	12.20	4	4
Twin Force Standard/424-210		Ortho Organizers, San Marcos, Calif., USA	1.286	90.00	90.00	62.00	44.00	12.62	261.44	566.57	20.70	44.90	4	4
Forsus fatigue resistant device, spring module universal (885-100) and push rod 32 mm (885-115)		3M-Unitek, Monrovia, Calif., USA	1.272	83.00	90.00	52.30	39.67	12.48	60.61	86.71	4.90	6.95	4	4
Hyrax II screw Mini/602-800-30	Expansion screw	Dentaurum, Ispringen, Germany	4.922	33.33	43.83			48.29	31.74	46.35	0.66	0.96	4	4
Compound palatal bar SE/NiTi-stainless steel/315-2003	Transpalatal arch	Forestadent, Pforzheim, Germany	0.776	81.83	90.00	48.00	42.33	7.61	46.57	90.81	6.10	11.90	4	4
Distal loop palatal/49-530-45		GAC, Central Islip, N.Y., USA	0.422	72.17	84.50	48.00	37.00	4.14	14.29	28.98	3.50	7.00	3	4

Table 1 (continued)

Name/ specification/ order number	Device	Manufacturer	Weight (g)	Deflection angle β [°] 1.5 T	Deflection angle β [°] 3 T	Corrected angle β [°]* 1.5 T	Corrected angle β [°]* 3 T	Gravity F_g [mN]	Translational force F_z 1.5 T	Translational force F_z 3 T	Ratio F_g/F_z 1.5 T	Ratio F_g/F_z 3 T	Torque F_{rot} 1.5	Torque F_{rot} 3T
Coated/size 1/09-045-11	Lip bumper	GAC, Central Islip, N.Y., USA	1.126	75.00	90.00	54.00	42.00	11.05	62.43	92.85	5.65	8.40	4	4
Custom made, 0.036″ hard Menzanium wire (18% Cr, 18% MN, 2% Mo, 1% Ni, iron)/8455/2	Quadhelix	Scheu-Dental, Iserlohn, Germany	0.740	0.00	5.33			7.26	0.00	0.68	0.00	0.09	0	0
Vertical lingual arch 0.036″, 62 mm/305-162	Lingual arch	3M-Unitek, Monrovia, Calif., USA	0.560	70.87	90.00	50.00	41.00	5.49	16.95	34.61	3.10	6.30	3	4
Split crimpable 0.018×0.025″/518-610	Archwire stop	3M-Unitek, Monrovia, Calif., USA	0.069	3.33	9.00			0.68	0.04	0.11	0.06	0.16	0	0

* Nonferromagnetic weights were attached to the objects

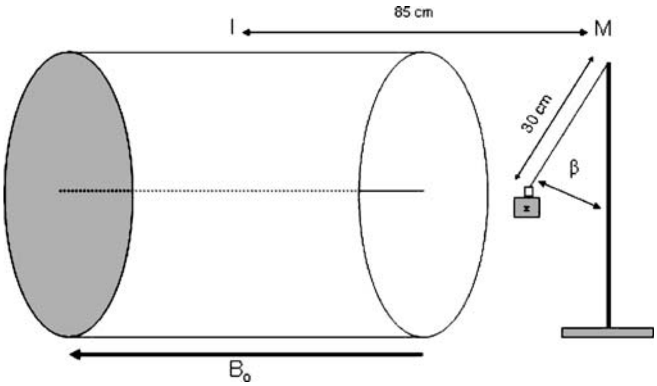

Fig. 1 Experimental set-up for the quantitative assessment of the translational force F_z by the “deflection angle test”. The estimation of the deflection angle β was carried out according to the ASTM guideline F2052-02

effect of torque F_{rot} is known to be greatest [6, 9, 16]. The object was observed, and any alignment or rotation was rated. The object was then moved 45° relative to its previous position and again observed for alignment and rotation. This procedure was repeated to encompass a full 360° rotation of positions for each device. Measurements were repeated three times for each object and averaged. For the assessment of torque the established qualitative scale was used (Table 2) [9–11, 17–19].

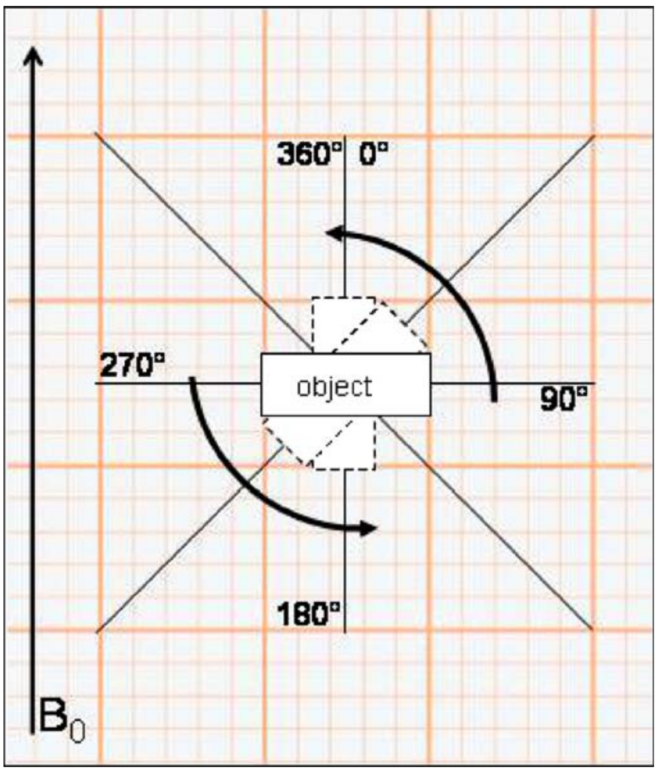

Fig. 2 Experimental set-up for the qualitative assessment of the rotational force F_{rot} (top view)

Table 2 Assessment of torque using the established qualitative scale

Scale	Definition
0	No torque
+1	Mild torque; the test object slightly changed orientation but did not align to the magnetic field
+2	Moderate torque; the test object aligned gradually to the magnetic field
+3	Strong torque; the test object showed rapid and forceful alignment to the magnetic field
+4	Very strong torque; the test object showed very rapid and very forceful alignment to the magnetic field

Results

The findings for magnetic field interactions for the orthodontic objects exposed to the 1.5- and 3-T MR systems are summarized in Table 1. These include deflection angle β, resulting translational force F_z, assessment of torque F_{rot}, and the ratio of translational force F_z and gravitational force F_g.

In 12/20 (13/20) objects, the deflection angle exceeded 65° at 1.5 (3) T. For these objects, additional measurements with attached nonferromagnetic weights were complemented.

At 1.5-T, 13 of 20 (65%) stainless steel devices were highly ferromagnetic with deflection angles ≥45° and a torque value of +3/4 (15.4%) or +4/4 (84.6%). Translational forces on these appliances ranged between 10.2 mN (Hi-T II coil spring open-space wound 0.010", 3M-Unitek, Monrovia, CA, USA) and 261.4 mN (Twin Force Standard 424-210, Ortho Organizers, San Marcos, CA, USA). Translational force Fz was found to be up to 24.1 times higher than gravitational force F_g. The remainder of the devices (35%) were characterized by weaker magnetic field interactions with deflection angles between 0° and 33.3°. However, even within this group, three devices showed torque forces F_{rot} of +3/4 or +4/4.

At 3 T, 15 of 20 (75%) objects were highly ferromagnetic with deflection angles ≥45° and torque values of +3/4 (6.7%) and +4/4 (93.3%). Translational forces on these appliances ranged between 20.1 mN (Hi-T II coil spring open-space wound 0.010", 3M-Unitek) and 566.6 mN (Twin Force Standard 424-210, Ortho Organizers). Translational force F_z was found to be up to 47.5-fold higher than gravitational force Fg. The remaining five orthodontic objects (25%) showed weaker or no magnetic field interactions (β = 0° – 43.8°). However, one of these five devices also showed high torque force (+4/4).

The Pearson correlation r coefficient between the translational forces F_z at 1.5 and 3.0 T was 0.99 (Fig. 3).

No magnetic field interactions were found for the Sentalloy open coil spring (medium/10-000-08, GAC, Central Islip, NY, USA) at the 1.5- and 3-T field strengths, respectively.

Out of 20 objects investigated for translational forces at 1.5 (3) T, 13 (15) may be considered "not MR safe" in the MR environment, based on the ASTM criteria [7].

Discussion

The possible interaction between a ferromagnetic object and the static magnetic field of an MR system is an important safety consideration in clinical MR imaging. The term "MR safe" indicates that the device, when used in the MR environment within the 5 Gs line, has been demonstrated to present no additional risk to the patient or other personnel but may affect the quality of the diagnostic information [20].

Interactions between a ferromagnetic object and the static magnetic field of an MR system include displacement force F_z, a translational force caused by exposure of ferromagnetic material to the spatial gradient of the magnetic field, and torque F_{rot}, the tendency of the object to rotate or align itself relative to the magnetic field [5, 6, 16]. The magnitude of these interactions is proportional to the field strength and spatial field gradient of the MR system, as well as the characteristics of the object itself, including the mass, shape, and the object's magnetic susceptibility.

Fixed orthodontic appliances consist of a number of parts that are connected to each other and are used for adjusting the occlusion of the jaw or to move one or more teeth (Fig. 4). Many times, patients undergoing MR procedures are in active orthodontic therapy with fixed appliances. The knowledge of safety risks for these patients is of high practical relevance and often difficult to assess for the radiologist. Mobile and completely removable orthodontic devices do not cause problems and can easily be eliminated prior to an MRI examination [1, 21]. For orthodontic bands and brackets, forces due to the MR magnetic field require that these objects be carefully checked for a secure attachment e.g. by adhesive bonding to the tooth surface or by wire ligation of the individual parts [3, 4]. Auxiliary orthodontic parts are attached to the fixed orthodontic appliance by different means and often cannot be removed without considerable effort, costs and interruption of orthodontic therapy. These metallic orthodontic devices are important components in modern fixed orthodontic therapy.

It is well known that magnetic field-related forces may cause hazards to patients and individuals with ferromagnetic implants or devices [22, 23]. Considerable discom-

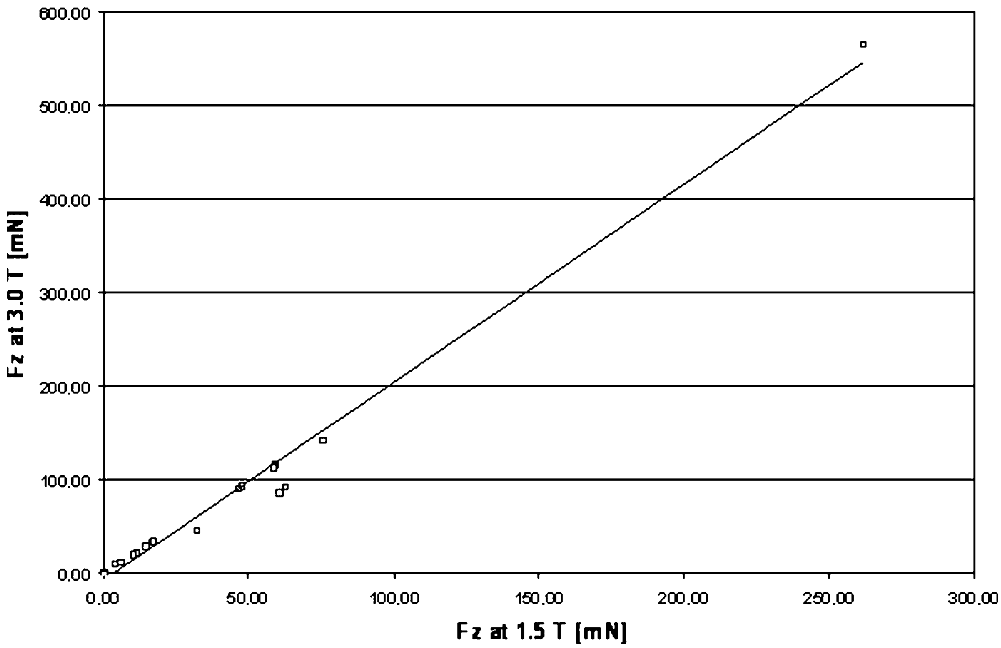

Fig. 3 Correlation of translational forces measured at 1.5 T and 3 T. The amount of force almost doubled when the field strengths of 1.5 T and 3 T were compared

fort, even injury or aspiration, can occur in a patient who has orthodontic appliances that exhibit substantial force or torque in association with exposure to the magnetic field. The potential danger is underlined by the maximum amount of translational force F_z, which was found to be up to 47.5-times higher than gravitation.

The present study analysed magnetic field interactions of 20 different orthodontic appliances exposed to 1.5 T and 3 T MR systems, with a view to assess important elements of MR safety information. Therefore, we assessed different orthodontic parts of the fixed appliance made from different alloys and used for various clinical indications.

The deflection angle test is an integral component in the safety estimation of medical implants and devices within the magnetic field of MRI systems [6, 9–11]. This test has been shown to become increasingly inaccurate with deflection angles exceeding 65° [8, 12]. With many of the devices tested, the maximum deflection angle of 90° was reached. Therefore, we repeated the measurements with non-ferromagnetic weights to reduce the deflection angle to below 65° [12]. This modification of the deflection angle test allows the assessment of the translational force even on strongly ferromagnetic objects. According to the ASTM standard, all devices with a deflection angle ≥45° are classified as "not MR safe". The reason for this upper limit is traced back to the fact that, in those objects, translational force F_z exceeds gravitational force F_g. In other words, a force that causes an acceleration >1 g would hoist an object and accelerate it towards the magnet (so-called "missile effect"). At 1.5 T and 3.0 T, 13 (65%) and 15 (75%), respectively, of the appliances investigated have to be classified as "not MR safe". As expected, displacement forces for the tested devices were greater during exposure to the higher field strength. The ascertained translational force F_z approximately doubled when the two different field strengths were compared. This effect can be expected, given that the translational force F_z increases in proportion to magnetic field strength. The fact that they do not exactly double might be caused by measurement errors due to field inhomogeneities or by the gradient design and configuration of the two different MR scanner systems from different manufacturers. It should be noted that, because of design differences in magnets (e.g. magnetic shielding) used for MR systems, the findings for translational forces of the objects tested are specific to these scanners or to MR systems, with comparable spatial gradients and shielding of the main static magnetic field. However, the strong correlation of the translational forces at 1.5 T and 3.0 T indicates consistent measurements (Fig. 3). It is important to note that a medical device that is safe in or compatible with a 1.5 T scanner might not be so in a 3 T system [7]. One intermaxillary spring (Flex Developer, LPI-Ormco, Austria) and the Herbst appliance (Herbst I, telescope and screw/607-100-00, Dentaurum, Germany) were affected by this phenomenon and became "MR unsafe" only at 3.0 T.

An F_z/F_g ratio >1.0 does not necessarily mean that this object is harmful within the MRI system's magnetic field [24]. The intended "in vivo use" of an object has to be considered [5]. Counterforces play an important role and can effectively prevent the device from presenting a substantial risk or hazard to the patient in the MR environment [5, 6]. Auxiliary parts of the orthodontic appliance are typically attached in such a way that they can withstand considerable forces (e.g. during chewing). These parts are unlikely to be dislodged by forces generated by the static magnetic field of a 1.5 T or a 3 T MR

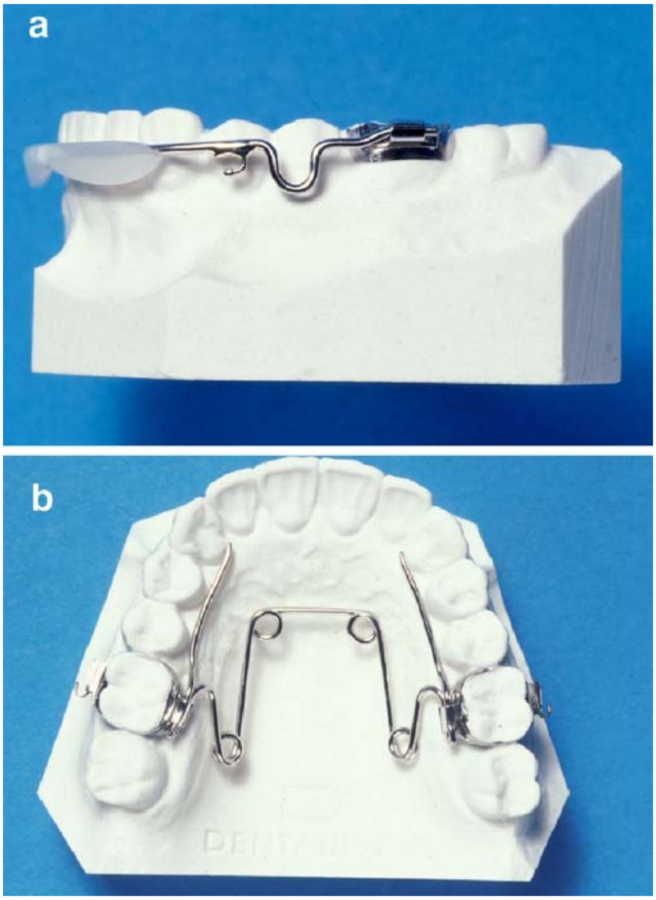

Fig. 4 **a** The lip bumper appliance is inserted into tubes attached to molar bands. While the molar band is cemented to the tooth, the lip bumper appliance can be removed by the patient. **b** The Quadhelix appliance is placed in the palatal region of the mouth. It is typically inserted by the orthodontist into sheaths attached to the molar bands. Sometimes, elastomeric or wire ligatures are used to secure the attachments of the Quadhelix to the molar bands

scanner. Nevertheless, to exclude a potentially fatal disconnection or loosening of an orthodontic device, the orthodontic inspection of the fixation of the ligated parts prior to and after a MR examination is mandatory. On the other hand, the lip bumper appliance is generally only loosely inserted by finger pressure and can be removed by the patient for eating and brushing. This type of appliance should be removed from the patient's mouth prior to an MR investigation.

With regard to magnetically induced torque the rotational force F_{rot} did not differ substantially between the 1.5 T and 3 T systems. Torque, which develops when a non-spherical object is exposed to a magnetic field, occurs in a direction such that the long axis of a ferromagnetic device will tend to align along the direction of the magnetic field. The maximum torque will be independent of the field strengths, assuming that the field is sufficiently strong to magnetically saturate the object [24, 25]. The torque is nearly zero when the long axis is aligned along the field and is maximal when the long axis is approximately perpendicular to the static magnetic field. Because of the shape of an orthodontic object, the maximum torque will depend on the orientation of the object. The orientation effect can be dramatic, and it has to be noticed that F_{rot} permanently takes effect on the object during the MR examination in the isocentre of the magnet, whereas translational force F_z just interferes when the patient is moved in or out of the magnet. At this point it has to be mentioned that the applied qualitative assessment of the torque is a drawback of the data presented. The ASTM standard test F2213-04 for the quantitative measurement of magnetically induced torque based on a torsional spring could not be applied due to the small size of the orthodontic objects [13]. Therefore, a qualitative assessment of torque had to be applied using the established 5-point grading scale (Table 2), which was originally introduced by Nogueira and Shellock in 1994 [14].

With respect to the clinical implications of this study, the risks involved when a patient with an orthodontic device is exposed to an MRI procedure must be weighed against the clinical or diagnostic benefit to be derived from the examination. All forces on auxiliary orthodontic appliances due to magnetic field interactions were found to be below 1 N (maximum 0.567 N; intermaxillary spring, Twin Force Standard/424-210, Ortho Organizers) and, thus, are unlikely to compromise a sufficient attachment of these objects to other parts of the appliance or the tooth surface. The magnitude of magnetically induced forces on some of the appliances is comparable to the lower range of forces applied in orthodontic treatment to induce tooth movement. Therefore, it is likely that, when undergoing MRI procedures, some patients with fixed orthodontic appliances will experience sensations similar to those from the application of forces on the teeth during orthodontic treatment, i.e. a certain degree of discomfort.

Although the findings of the study provide important aspects for determining the risk–benefit ratio, other important effects have to be considered. Magnetic field interactions represent only one part of the information necessary to determine comprehensively the potential risk of exposing a patient with an orthodontic apparatus to the MRI environment. Other important factors, including heating and induced electrical currents, must be taken into account. Further studies are required for the evaluation of these issues.

In conclusion, the majority of the orthodontic devices investigated have to be classified as "not safe" in the MR environment at 1.5 T and 3 T based on the ASTM guideline for translational forces. Consequently, MR examinations of auxiliary orthodontic appliances are feasible only if their identity can be clearly assured. Loose orthodontic devices pose a significant danger for the patient.

However, the results show that the forces measured were small compared with those forces typically applied to these appliances in the patient's mouth. The potential risk should be minimised by accurate professional inspection for adequate fixation of the devices prior to the MR examination. Removable parts of the fixed appliance (e.g. the lip bumper) should be detached prior to the MR examination. Therefore, MR procedures on patients with fixed auxiliary orthodontic parts can be reasonable in individual cases provided that strict indication exists. Additional risk factors such as heating have to be considered for a comprehensive and ultimate risk estimation.

References

1. Okano Y, Yamashiro M, Kaneda T, Kasai K (2003) Magnetic resonance imaging diagnosis of the temporomandibular joint in patients with orthodontic appliances. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 95:255–263
2. http://www.MRIsafety.com
3. Kemper J, Klocke A, Kahl-Nieke B, Adam G (2005) Orthodontic brackets in high field MR imaging: experimental evaluation of magnetic field interactions at 3.0 Tesla. Fortschr Rontgenstr 177:1691–1698
4. Klocke A, Kemper J, Schulze D, Adam G, Kahl-Nieke B (2005) Magnetic field interactions of orthodontic wires during magnetic resonance imaging (MRI) at 1.5 Tesla. J Orofac Orthop 66:279–287
5. Shellock FG (2005) Reference manual for magnetic resonance safety, implants, and devices. In: 2005 edn, Biomedical Research Publishing Group, Los Angeles, pp 122–134
6. Shellock FG, Tkach JA, Ruggieri PM, Masaryk TJ (2003) Cardiac pacemakers, ICDs, and loop recorder: evaluation of translational attraction using conventional (“long-bore”) and “short-bore” 1.5- and 3.0-Tesla MR systems. J Cardiovasc Magn Reson 5:387–397
7. ASTM (2002) Designation: F2052-02. Standard test method for measurement of magnetically induced displacement force on medical devices in the magnetic resonance environment. In: Annual book of ASTM standards, West Conshohocken, pp 1576–1580
8. New PF, Rosen BR, Brady TJ et al (1983) Potential hazards and artifacts of ferromagnetic and nonferromagnetic surgical and dental materials and devices in nuclear magnetic resonance imaging. Radiology 147:139–148
9. Shellock FG, Shellock VJ (1999) Metallic stents: evaluation of MR imaging safety. AJR Am J Roentgenol 173: 543–547
10. Greatbatch W, Miller V, Shellock FG (2002) Magnetic resonance safety testing of a newly-developed fiber-optic cardiac pacing lead. J Magn Reson Imaging 16:97–103
11. Edwards MB, Taylor KM, Shellock FG (2000) Prosthetic heart valves: evaluation of magnetic field interactions, heating, and artifacts at 1.5 T. J Magn Reson Imaging 12:363–369
12. Kagetsu NJ, Litt AW (1991) Important considerations in measurement of attractive force on metallic implants in MR imagers. Radiology 179:505–508
13. ASTM (2002) Designation: F2213-04. Standard test method for measurement of magnetically induced torque on medical devices in the magnetic resonance environment. In: Annual book of ASTM standards, West Conshohocken, pp 1576–1580
14. Nogueira M, Shellock FG (1994) Otologic bioimplants: ex vivo assessment of ferromagnetism and artifacts at 1.5 T. AJR Am J Roentgenol 163:1472–1473
15. Shellock FG (1999) Metallic marking clips used after stereotactic breast biopsy: ex vivo testing of ferromagnetism, heating, and artifacts associated with MR imaging. AJR Am J Roentgenol 172:1417–1419
16. Planert J, Modler H, Vosshenrich R (1996) Measurements of magnetism-related forces and torque moments affecting medical instruments, implants, and foreign objects during magnetic resonance imaging at all degrees of freedom. Med Phys 23: 851–856
17. Sommer T, Maintz D, Schmiedel A et al (2004) High field MR imaging: magnetic field interactions of aneurysm clips, coronary artery stents and iliac artery stents with a 3.0 Tesla MR system. Fortschr Rontgenstr 176: 731–738
18. Kangarlu A, Shellock FG (2000) Aneurysm clips: evaluation of magnetic field interactions with an 8.0 T MR system. J Magn Reson Imaging 12:107–111
19. Shellock FG (2002) Biomedical implants and devices: assessment of magnetic field interactions with a 3.0-Tesla MR system. J Magn Reson Imaging 16:721–732
20. http://www.fda.gov/cdrh/
21. Sadowsky PL, Bernreuter W, Lakshminarayanan AV, Kenney P (1988) Orthodontic appliances and magnetic resonance imaging of the brain and temporomandibular joint. Angle Orthod 58:9–20
22. Colletti PM (2004) Size “H” oxygen cylinder: accidental MR projectile at 1.5 Tesla. J Magn Reson Imaging 19:141–143
23. Chaljub G, Kramer LA, Johnson RF 3rd, Johnson RF Jr, Singh H, Crow WN (2001) Projectile cylinder accidents resulting from the presence of ferromagnetic nitrous oxide or oxygen tanks in the MR suite. AJR Am J Roentgenol 177:27–30
24. Baker KB, Nyenhuis JA, Hrdlicka G, Rezai AR, Tkach JA, Shellock FG (2005) Neurostimulation systems: assessment of magnetic field interactions associated with 1.5- and 3-Tesla MR systems. J Magn Reson Imaging 21:72–77
25. Wittenauer MA, Nyenhuis JA, Schindler AI (2003) Growth and characterization of high purity single crystals of barium ferrite. J Cryst Growth 130:533–542