Induced magnetic moment in stainless steel components of orthodontic appliances in 1.5 T MRI scanners

Zhiyue J. Wang^{a)} and Nancy K. Rollins

Department of Radiology, Children's Medical Center, Dallas, Texas 75235 and Department of Radiology, University of Texas Southwestern Medical Center, Dallas, Texas 75390

Hui Liang

Baylor College of Dentistry, Texas A&M University, Dallas, Texas 75246

Yong Jong Park

Division of Orthodontics, Children's Medical Center, Dallas, Texas 75235

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Purpose: Most orthodontic appliances are made of stainless steel materials and induce severe magnetic susceptibility artifacts in brain MRI. In an effort for correcting these artifacts, it is important to know the value of induced magnetic moments in all parts of orthodontic appliances. In this study, the induced magnetic moment of stainless steel orthodontic brackets, molar bands, and arch-wires from several vendors is measured.

Methods: Individual stainless steel brackets, molar bands, and short segments of arch-wire were positioned in the center of spherical flask filled with water through a thin plastic rod. The induced magnetic moment at 1.5 T was determined by fitting the B_0 map to the z -component of the magnetic dipole field using a computer routine.

Results: The induced magnetic moment at 1.5 T was dominated by the longitudinal component m_z , with a small contribution from the transverse components. The m_z was insensitive to the orientation of the metal parts. The orthodontic brackets collectively dominated the magnetic dipole moment in orthodontic appliances. In brackets from six vendors, the total induced m_z from 20 brackets for nonmolar teeth ranged from 0.108 to 0.158 (median 0.122) A·m². The m_z in eight molar bands with bracket attachment from two vendors ranged from 0.0004 to 0.0166 (median 0.0035) A·m². Several full length arch wires had induced magnetic moment in the range of 0.006–0.025 (median 0.015) A·m².

Conclusions: Orthodontic brackets collectively contributed most to the total magnetic moment. Different types of brackets, molar bands, and arch wires all exhibit substantial variability in the induced magnetic moment. © 2015 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4930796>]

Key words: MRI artifacts, orthodontic appliances, stainless steel, induced magnetic moment

1. INTRODUCTION

A large proportion of the general population undergoes orthodontic treatment at some time during their lifetime, usually during adolescence. In this treatment, orthodontic wires are engaged to orthodontic brackets bonded on teeth. The interaction between the wires and brackets corrects the teeth positioning. Sometimes, orthodontic bands instead of brackets are used for molars. During the treatment, some patients unexpectedly undergo MRI for a new medical condition. Orthodontic appliances (commonly known as dental braces or braces) frequently contain stainless steel components which exhibit large induced magnetic moments inside the MRI scanner, causing susceptibility artifacts in brain images.^{1–8} These artifacts compromise the diagnostic value of the scan and can negatively impact the clinical outcome, especially in emergency situations such as in acute stroke or head trauma where there is a narrow window of time for effective therapeutic intervention.^{9,10} Removal of ferromagnetic orthodontic appliances for brain MRI is a com-

mon practice.^{11,12} However, emergency removal of the braces is usually impractical, and permanent removal may be needed for patients who need frequent follow up MRI studies such as in the case of brain tumors.¹¹ These artifacts have been known since early days of MRI, but there remains a technical gap in addressing them sufficiently. There are different brands of orthodontic brackets, molar bands, and arch wires in common use. Knowledge of magnetic properties of these parts will be valuable for predicting the severity of MRI artifacts and for attempting to decrease image artifacts. In addressing MRI artifacts, the directly relevant physical quantity is the magnetic moment, which determines the induced B_0 field inhomogeneity. Although there have been studies of magnetic forces and torques between brackets and MRI magnets,^{13–15} the focus of these studies was on MRI safety concerns, and the induced magnetic moment at the magnet's center was not of interest. Williams studied magnetic susceptibility of some orthodontic wires using an apparatus with an electromagnet.¹⁶ Behr *et al.* studied magnetic susceptibility of certain dental

alloys using a vibrating sample magnetometer and observed geometric distortion on spin echo MR images and signal loss on gradient echo images on a phantom embedded with dental alloys.¹⁷ There were also studies quantifying MRI artifacts from dental materials.¹⁸ From a diagnostic imaging physics viewpoint, detailed composition of commercial orthodontic brackets, bands, and wires in patients is not known, and the weights of these components are also variable. The induced magnetic moment is the quantity that directly relates to the B_0 inhomogeneity. Knowing the induced B_0 field inhomogeneity is helpful for designing MRI pulse sequences that are less prone to magnetic susceptibility artifacts and for other artifact correction strategies. The induced magnetic moments of currently used orthodontic appliances inside MRI scanners have not been reported previously. The purpose of this work is to fill this gap in knowledge for 1.5 T MRI scanners. We investigated orthodontic nonmolar brackets from six vendors (Ormco, 3M Unitek, GAC, Henry Schein, Speed, and American Orthodontics), molar brackets and bands from two vendors (Ormco, 3M Unitek), and arch-wires of different sizes from three vendors (Class One, 3M Unitek, Ormco). The results will be useful in guiding efforts for correcting MRI artifacts induced by orthodontic appliances.

2. METHODS

2.A. Components of orthodontic appliances

Orthodontic appliances consist of brackets that are in most cases bonded to the labial or lingual surfaces of teeth and arch wires that are engaged to brackets and exert forces moving the teeth. Sometimes bands are used in place of brackets for molars (Fig. 1). Titanium brackets and wires have been available which are more MRI friendly. There are also plastic or ceramic brackets that are free of MRI artifacts. However, stainless steel is still the most preferred material for orthodontic appliances due to its durable and reliable performance as well as low cost. Because teeth at different positions have different anatomies

FIG. 1. Components of orthodontic appliances are shown. All of these components are frequently made of stainless steel. (A) A dental model with orthodontic brackets mounted on 28 teeth. An arch wire is engaged to lower teeth. The arch wire for the upper teeth is not engaged. (B) An orthodontic arch wire. (C) Orthodontic bands with a bracket attached may be used to replace stand-alone brackets on molars.

TABLE I. Orthodontic brackets for nonmolar teeth from several major vendors were studied and the weights of these brackets (in mg units) are listed in the table. The right and left brackets were not distinguished in this study.

Tooth	Ormco (Orthos ^a)	3M Unitek (Victory Series, 0.022)	GAC (In- Ovation)	Henry Schein (Maestro, 0.022)	Speed (0.022)	AO (Mini Master, Alexander System)
Lower 1	64.1 ± 0.9	73	89	53	69	71
Lower 2	63.6 ± 0.8				72	
Lower 3	65.6 ± 0.6	84	91	63		61
Lower 4	64.4 ± 1.4	76	88	67	83	
Lower 5	65.0 ± 1.3	75	84	68	107	68
Upper 1	66.4 ± 1.1	77	94	63	70	53
Upper 2	62.5 ± 1.2	74	99	61	82	63
Upper 3	75.6 ± 0.9	80	93	59	96	55
Upper 4	67.4 ± 1.8			61		
Upper 5	58.4 ± 0.9	74	89	60	108	69

Note: AO = American Orthodontics; 1 = central incisor; 2 = lateral incisor; 3 = canine; 4 = first premolar; 5 = second premolar.

^an = 8, mean ± SD.

from each other, specific brackets are used for each tooth, with right and left sides being mirror images of each other. In this study, nonmolar brackets from six vendors (listed in Table I together with the weight) and molar brackets and bands from two vendors (Table II) were investigated. In addition, we also studied various arch wires from Class One, 3M Unitek and Ormco. The full length of these arch wires ranged from 15.5 to 19.3 cm. The wires had either round cross section (diameter ranged from 0.014 to 0.018 in.) or rectangular cross section (height × width ranged from 0.016 × 0.022 to 0.018 × 0.025 in.²).

2.B. Measurement of induced magnetic moments using MRI

Orthodontic brackets or molar bands were measured one at a time. The measurement setup for one bracket is shown in Fig. 2. A sample was glued using epoxy adhesives to the end surface of an acrylic plastic rod with a diameter of 4.75 mm. The end surface was flat and perpendicular to the axis of the rod. The rod was inserted into the center of a 2-l spherical glass flask containing water. The epoxy glue and plastic rod did not produce observable magnetic susceptibility effects on the measurements. Two cc ProHance (Gadoteridol, Bracco

TABLE II. Molar brackets and molar bands investigated in this work and their weights.

Parts	Ormco (Peerless bracket)		Ormco (band with bracket)		3M Unitek (band with bracket)	
	Lower 6, upper 6	Lower 7, upper 7	Lower (n = 2)	Upper (n = 2)	Lower (n = 2)	Upper (n = 2)
Weight (mg)	110, 119	62, 61	310, 315	438, 446	233, 263	306, 466

Note: 6 = first molar; 7: second molar.

FIG. 2. MRI measurement setup: (A) a bracket was glued to the end of a plastic rod. (B) The plastic rod was inserted into a water filled 2-l flask to position the bracket at the center. The flask would be moved to the center of MRI scanner for measurement. For a central incisor bracket, the orientation corresponds to that of a person entering scanner with head first and in prone position. (C) For the study on the orientation dependence of the induced magnetic moment, the flask was rotated about the X- and Y-axes by $\pm 30^\circ$, respectively. X-axis is in the horizontal direction, Y-axis is in the vertical direction, and B_0 field is along the Z-axis.

Diagnostic, Inc.) was used to shorten T_1 of the solution leading to SNR improvement. For arch-wires, a short segment was glued to the tip of plastic rod and measured by MRI to obtain the magnetic moment per unit length. The lengths of the short wire segment ranged from 7 to 8 mm.

The flask was positioned at the center of a 1.5 T Philips Achieva MRI scanner, and the offset B_0 field distribution (the offset to the 1.5 T uniform background B_0 field) inside it was measured using 3D sagittal fast gradient echo (FFE) sequences using the Q-body coil. The 3D FFE sequences were used instead of a multislice 2D acquisition mainly for the SNR advantage. Two image sets with slightly different echo times were acquired. Data acquisition parameters were TR (ms)/TE (ms)/flip angle ($^\circ$) = 10/3.5/3.8/10, FOV = 224 mm, voxel = $2 \times 2 \times 2$ mm³, 75 slices, WFS = 0.26 pixels, phase encoding direction = AP, and NSA = 1. The echo times were near the minimum allowed by the scanner, and a small increment in TE ensured that there was no phase wrap-around in the difference phase map. Complex MRI images in DICOM format were copied from the MRI scanner to an offline workstation.

The data analysis was performed using internally developed software written in IDL 8.0. The 3D map of the z-component of the static magnetic field offset ΔB_z was obtained from the difference of phase images at the two echo times and modeled using a magnetic dipole,¹⁹

$$\Delta B_z = \frac{\mu_0}{4\pi} \frac{3n_z(\mathbf{n} \cdot \mathbf{m}) - m_z}{|\mathbf{x}|^3} + P_2(\mathbf{x}). \quad (1)$$

Here, $\mu_0 = 4\pi \times 10^{-7}$ T·m/A is the permeability of free space, $\mathbf{x}$ is a displacement vector from the location of the dipole to a point in space where the field was measured, $\mathbf{n} = (n_x, n_y, n_z)$ is a unit vector along the direction of $\mathbf{x}$, and $\mathbf{m} = (m_x, m_y, m_z)$ is the induced magnetic moment to be determined by a least squares fitting routine. The contribution from background shimming imperfection and the field offset was included in Eq. (1) as $P_2(\mathbf{x})$ which is a second order polynomial of x , y , and z coordinates. Image pixels with signal amplitude less than 50% of maximum were excluded from the model fitting. The ΔB_z map was fitted to Eq. (1) with a least squares procedure (IDL routine “curvefit”) using a gradient expansion method²⁰

adapted from the algorithm described by Marquardt²¹ and using double precision variables. The computer routine returned the location of the magnetic dipole, second order background field, and the magnetic moment of the sample, $\mathbf{m} = (m_x, m_y, m_z)$, which was recorded. Figure 3 demonstrates the MRI B_0 offset field mapping and fitting using this magnetic dipole model [Eq. (1)].

2.C. Testing the measurement of both transverse and longitudinal components of magnetic moment in permanent magnet

The measurement procedure was tested by measuring the magnetic moment of a NdFeB permanent magnet²² (grade N3830, Dexter Magnetic Technologies, <http://www.dexter-mag.com/N3830>), with the shape of rectangular prism and dimensions of $1.3 \times 1.3 \times 5.0$ mm³ with Ni coating and fully magnetized along the long axis. This material has an intrinsic coercivity of 2387 kA/m (corresponding to 3 T in a vacuum) at 20 °C and can resist irreversible demagnetization inside 1.5 T MRI scanners. When the magnetic moment of the permanent magnet was parallel or antiparallel to the B_0 field, the measured magnetic moment was $\mathbf{m} = (-0.9, -1.2, 78.3) \times 10^{-4}$ A·m² and $(3.4, -2.3, -60.2) \times 10^{-4}$ A·m², respectively. The measured magnetic moment was predominantly along the z direction and the residual transverse components likely came from imperfect alignment. The amplitude of m_z was expected to decrease when the orientation was antiparallel to B_0 because of the reversible demagnetization caused by the MRI scanner field. The m_z was expected to increase when the orientation was parallel to B_0 because the magnetization was enhanced by B_0 field. When the permanent magnet was perpendicular to the B_0 field (long axis along the x -direction), the measured magnetic moment was $\mathbf{m} = (70.2, -3.4, 20.8) \times 10^{-4}$ A·m². Remembering that the permanent magnet has the magnetization along its long axis, we note that the m_x value in this orientation was the magnetic moment along the original magnetizing direction with a perpendicular external field. In this case, the magnetic moment along the long axis, as we expected, was about halfway between the values when the external B_0 field was parallel or antiparallel to the magnetization of the

FIG. 3. Measurement of magnetic moment of an Ormco Orthos lower left central incisor orthodontic bracket using 3D FFE is demonstrated here. An amplitude image is shown in (A) where four central sagittal slices were averaged to enhance SNR for demonstration purpose. Signals in the near vicinity of the bracket at the center were destroyed, and the dark line on the left came from the plastic rod holding the bracket. The measured ΔB_z map obtained using the phase difference image from data with TE of 3.8 and 3.5 ms was shown in (B), where areas with signal amplitude less than 50% of the maximum were excluded, and there was no phase wrap around in the phase difference image. The resulting fit of ΔB_z using Eq. (1) is shown in (C).

sample. There was also a substantial m_z component coming from reversible magnetization by the B_0 field.

The measurement was performed at a temperature of 25 °C where the residual flux density (also known as remanence) B_r at zero external magnetic fields is 1.24 T for the sample we used (<http://www.dextermag.com/N3830>), and the magnetization is given by B_r/μ_0 ,^{19,23} assuming there was no demagnetization field effects and ignoring small shielding of the field by the Ni coating. The magnetic moment of the permanent magnet can be calculated as $B_r \times \text{volume}/\mu_0 = 83 \times 10^{-4} \text{ A}\cdot\text{m}^2$. The demagnetization field and shielding effects should both slightly decrease the actually observed magnetic moment. We assume that the magnetic moment of the sample at a zero external field can be obtained by an average value for situations with a parallel or antiparallel external field, which equaled to $69.3 \times 10^{-4} \text{ A}\cdot\text{m}^2$. This value agreed with the simplified theoretical value within 16.5%. Therefore, we believe the measurement procedure was able to quantify both the longitudinal and transverse components of the magnetic moment.

2.D. Repeatability and reproducibility of the measurements

We use the terms “repeatability” and “reproducibility” according to Kessler et al.²⁴ The repeatability of the measurement was tested using an Ormco Orthos bracket for the lower left central incisor using 2 Philips 1.5 T Achieva MRI scanners using identical acquisition parameters on three sessions. The results are listed in Table III. The SD of repeated measurements without repositioning the setup was $(0.01, 0.03, 0.09) \times 10^{-4} \text{ A}\cdot\text{m}^2$. When the setup is repositioned between the repeats, the standard deviation of the repeated measurements was $(0.07, 0.23, 0.36) \times 10^{-4} \text{ A}\cdot\text{m}^2$. The overall range of m_z

measured on three days on the two scanners was 62.1–64.1 $\times 10^{-4} \text{ A}\cdot\text{m}^2$. The coefficient of variation was 1.2% for all m_z measurements with reposition in Table III.

2.E. Orientation dependence measurements

Because components of orthodontic appliance may assume variable orientations when mounted on the teeth of patients, we also studied whether the results are sensitive to the orientation of the metal parts. In one set of Ormco Orthos and one set of Ormco Peerless buccal tube brackets, the induced magnetic moments were measured in five orientations including straight, $\pm 30^\circ$ roll angle [for a front tooth bracket, positive roll angle corresponds to tilting head sideways toward right, as shown in Fig. 2(C)] and $\pm 30^\circ$ pitch angle [on a front tooth, a positive angle for chin up as in Fig. 2(C)]. The orientation dependence of stainless steel arch wires was tested on Class One wires of three sizes. The magnetic moment of a wire segment was measured with the segment parallel and perpendicular to the B_0 field.

3. RESULTS

3.A. Orientation dependence of the induced magnetic moment

The results of orientation dependence of induced magnetic moment in Ormco brackets are listed in Table IV. In this table, the magnetic moment of the Peerless brackets was much smaller than that of Orthos brackets, due to the fact that they are made of different types of stainless steels with different elemental compositions. Furthermore, the transverse components of the induced magnetic moments were much smaller

TABLE III. Measured magnetic moments (m_x, m_y, m_z) in units of $10^{-4} \text{ A}\cdot\text{m}^2$ at different times.

	First scan	Second scan	Third scan	Fourth scan
Scanner 1, day 1	(0.08, -0.81, 62.06)			
Scanner 1, day 2 ^a	(-0.17, -0.75, 62.25)	(-0.17, -0.77, 62.12)	(-0.15, -0.83, 62.27)	(-0.17, -0.80, 62.09)
Scanner 2, day 3 ^b	(0.36, -1.28, 63.41)	(0.32, -1.19, 64.07)	(0.44, -0.78, 63.27)	(0.28, -0.95, 63.41)

^aScans were repeated without repositioning the setup.
^bScans were repeated with the setup repositioned.

TABLE IV. The induced magnetic moment (m_x, m_y, m_z) in units of 10^{-4} A·m² for one set of Ormco Orthos brackets (LL1–LL5, LR1–LR5, UL1–UL5, and UR1–UR5) and Ormco Peerless buccal tube brackets (LL6,7, LR6,7, UL6,7, and UR6,7). The last column lists the mean and SD for four different bracket orientations: $\pm 30^\circ$ roll angle and $\pm 30^\circ$ pitch angle.

Bracket	Bracket at a straight orientation	Mean $\pm$ SD for four rotated orientations
LL1	(−0.1, −1.5, 65.5)	(0.2 $\pm$ 1.3, 0.8 $\pm$ 0.9, 62.5 $\pm$ 1.3)
LL2	(−0.1, −0.5, 62.6)	(0.4 $\pm$ 1.4, 0.6 $\pm$ 0.4, 63.7 $\pm$ 1.6)
LL3	(−1.5, −0.4, 72.0)	(−0.9 $\pm$ 1.1, 0.4 $\pm$ 2.7, 69.7 $\pm$ 1.5)
LL4	(−0.2, −1.0, 53.3)	(−0.1 $\pm$ 0.8, 0.5 $\pm$ 2.7, 53.1 $\pm$ 0.2)
LL5	(−0.7, −2.1, 57.4)	(−0.6 $\pm$ 0.7, 1.4 $\pm$ 2.6, 58.4 $\pm$ 1.9)
UL1	(1.3, −1.9, 65.1)	(0.6 $\pm$ 0.4, 1.6 $\pm$ 0.4, 64.0 $\pm$ 1.2)
UL2	(1.9, −1.2, 62.7)	(1.2 $\pm$ 1.0, 1.2 $\pm$ 0.7, 61.9 $\pm$ 1.8)
UL3	(1.7, 1.1, 67.8)	(1.1 $\pm$ 0.7, 0.0 $\pm$ 2.8, 68.0 $\pm$ 0.6)
UL4	(0.0, −0.4, 63.2)	(0.0 $\pm$ 0.6, 0.5 $\pm$ 2.0, 62.3 $\pm$ 1.2)
UL5	(−0.3, −0.4, 55.1)	(−0.3 $\pm$ 0.7, 0.6 $\pm$ 1.8, 54.9 $\pm$ 0.3)
LR1	(0.0, −0.6, 66.0)	(0.1 $\pm$ 1.3, 1.0 $\pm$ 0.5, 67.1 $\pm$ 1.9)
LR2	(0.0, −1.4, 61.5)	(−0.2 $\pm$ 1.5, 0.4 $\pm$ 0.7, 60.2 $\pm$ 0.2)
LR3	(0.6, −0.7, 58.4)	(0.3 $\pm$ 0.9, 0.3 $\pm$ 1.9, 55.3 $\pm$ 0.5)
LR4	(0.1, −0.8, 58.1)	(−0.1 $\pm$ 0.4, 0.3 $\pm$ 2.8, 58.7 $\pm$ 1.6)
LR5	(0.0, −1.1, 56.1)	(0.0 $\pm$ 0.8, 0.9 $\pm$ 2.0, 56.0 $\pm$ 0.3)
UR1	(−0.9, −2.1, 62.1)	(−0.5 $\pm$ 0.5, 1.5 $\pm$ 2.1, 61.7 $\pm$ 0.4)
UR2	(−1.4, −2.1, 59.0)	(−1.1 $\pm$ 0.7, 0.8 $\pm$ 0.9, 59.3 $\pm$ 0.6)
UR3	(−2.4, −0.6, 76.3)	(−1.2 $\pm$ 0.9, 0.4 $\pm$ 3.8, 75.1 $\pm$ 2.5)
UR4	(0.0, −0.7, 64.6)	(−1.2 $\pm$ 2.4, 0.3 $\pm$ 2.1, 60.6 $\pm$ 0.4)
UR5	(0.2, −0.6, 54.5)	(0.0 $\pm$ 0.3, 0.0 $\pm$ 2.1, 54.8 $\pm$ 1.3)
LL6	(0.0, 0.1, 2.7)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.1, 2.6 $\pm$ 0.0)
LL7	(0.0, 0.0, 1.4)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.0, 1.4 $\pm$ 0.0)
UL6	(0.0, 0.0, 2.9)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.1, 3.0 $\pm$ 0.0)
UL7	(0.0, 0.0, 1.0)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.0, 1.0 $\pm$ 0.0)
LR6	(0.0, 0.0, 3.0)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.1, 3.1 $\pm$ 0.0)
LR7	(0.0, 0.0, 1.0)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.0, 1.0 $\pm$ 0.0)
UR6	(0.0, 0.1, 3.4)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.0, 3.4 $\pm$ 0.1)
UR7	(0.0, 0.0, 1.2)	(0.0 $\pm$ 0.0, 0.0 $\pm$ 0.0, 1.3 $\pm$ 0.0)

Note: LL = lower left; UL = upper left; LR = lower right; UR = upper right; 1 = central incisor; 2 = lateral incisor; 3 = canine; 4 = first premolar; 5 = second premolar; 6 = first molar; 7 = second molar.

than the longitudinal component. Table V shows the longitudinal and transverse components of the magnetic moment for each orientation averaged over Ormco Orthos brackets. Similar average data on Ormco Peerless brackets were not presented because of their low magnetic moment. The random errors in individual measurements were averaged out in the mean values which showed that the m_z value was not sensitive to the orientation of brackets relative to the B_0 field with a coefficient of variation of 0.6% for five orientations. In addition,

TABLE V. Average orientation dependence of the induced longitudinal and transverse components of magnetic moment in units of 10^{-4} A·m² for one set of 20 Ormco Orthos brackets. The average m_z and m_{xy} ^a are listed.

	Straight	−30° roll angle	30° roll angle	−30° pitch angle	30° pitch angle
$\langle m_z \rangle_{av}$	62.1	61.6	61.2	61.2	61.4
$\langle m_{xy} \rangle_{av}$	1.4	1.3	1.5	2.2	2.9

$$^a m_{xy} = (m_x^2 + m_y^2)^{0.5}.$$

TABLE VI. Orientation dependence of the induced magnetic moment (m_x, m_y, m_z) in units of 10^{-4} A·m² for “Class 1” arch wire segments.

Wire cross sectional size (in.)	Segment length (in.) ^a	Segment parallel to B_0	Segment perpendicular to B_0
Diameter = 0.014	0.29	(0.0, 0.1, 3.1)	(0.3, −0.1, 3.1)
Diameter = 0.018	0.28	(0.0, 0.0, 5.3)	(−0.2, −0.1, 5.4)
Height $\times$ width = 0.016 $\times$ 0.022	0.32	(0.1, −0.1, 7.6)	(−0.3, −0.1, 7.7)

^aThe length of the segment is estimated from the weight, knowing the total length and weight of the wire before cutting.

on average, the transverse component was no more than 5% of the longitudinal component.

The results of orientation dependence of induced magnetic moments in arch wires are listed in Table VI. Again, the induced magnetic moment was not sensitive to the orientation of the wire segment. The induced magnetic moments were insensitive to the orientation for molar bands as well (details not shown).

3.B. Induced longitudinal magnetic moment in parts of orthodontic appliances from several vendors

As shown in Tables IV and V, the induced magnetic moment was mainly along the longitudinal direction and not sensitive to the bracket orientation relative to the B_0 field. Therefore, we report results on m_z in a straight orientation. Table VII contains results of brackets for nonmolar teeth because brackets were often unavailable to this study for molars in many models. In Table VII, the right and left brackets were not distinguished, and in most cases, only one side was measured. Sometimes, neighboring teeth use the same brackets construction, and the measurements were not duplicated. The total induced magnetic moment of 20 brackets for each brand studied was listed in the last row in the table. The transverse components of the induced magnetic moment are much smaller than the longitudinal component for all brackets (not included in Table VII).

The induced magnetic moments of molar brackets and bands are listed in Table VIII. There was a large range of variability of the measured values within the same brand for molar bands attached with brackets, especially for parts from 3M Unitek. The total induced magnetic moment m_z of full length arch wires was estimated and shown in Table IX. Results from short segments perpendicular to B_0 field were converted to the total m_z of a full length wire.

4. DISCUSSION

In typical magnetic resonance imaging, spins are excited by band selective RF pulses in the presence of spatial encoding field gradient. Excited spins precess in the B_0 magnetic field with the Larmor frequency. The signals are acquired in the presence of a frequency encoding gradient. Excessive B_0 inhomogeneity on a macroscopic scale, such as that induced by ferromagnetic dental implants and braces, interferes with

TABLE VII. Induced m_z (10^{-4} A·m²) for dental brackets from six major vendors.

Tooth	3M (Victory Series, 0.022)			Henry Schein (Maestro, 0.022)		Speed (0.022)	AO ^a (Mini Master, Alexander system)
	Ormco (Orthos)		GAC (In-Ovation)				
Lower 1	64.5 ± 0.7 ^b					59.6	
Lower 2	63.9 ± 0.7 ^b	60.6	83.2	47.2		55.8	75.8
Lower 3	65.4 ± 2.5 ^b	77.2	84.1	54.1		58.5	42.5
Lower 4	60.9 ± 1.7 ^b	65.9	73.0	59.5			57.2
Lower 5	59.6 ± 1.2 ^b	69.2	77.9	60.0		52.5	
Upper 1	65.4 ± 0.9 ^b	65.1	75.4	52.6		60.5	43.3
Upper 2	60.8 ± 1.7 ^b	76.6	88.0	57.1		60.3	48.6
Upper 3	74.8 ± 1.6 ^b	82.9	77.0	51.5		56.8	42.9
Upper 4	62.4 ± 1.2 ^b			56.7			
Upper 5	55.3 ± 0.4 ^b	66.4	73.0	56.2		68.5	59.6
Mean ± SD of the bracket set	63.3 ± 5.1	69.1 ± 7.4	78.8 ± 5.5	54.2 ± 4.8		58.8 ± 4.2	56.3 ± 12.4
Total of 20 brackets	1266	1382	1576	1084		1176	1125

Note: 1 = central incisor; 2 = lateral incisor; 3 = canine; 4 = first premolar; 5 = second premolar.

^aAO = American Orthodontics.

^bMean ± SEM ($n = 8$).

each of these steps and causes MRI artifacts. It also causes excessive line broadening in MR spectroscopy which requires a high degree of B_0 homogeneity. Different imaging techniques are prone to the artifacts with different sensitivity and through different mechanisms.²⁵ The B_0 shimming capability of scanners is unable to remove artifacts from magnetic orthodontic appliances. Much effort has been made to design pulse sequences that are immune to magnetic susceptibility artifacts. Some of these techniques are available for clinical examinations. For example, single-shot turbo spin-echo diffusion-weighted imaging could be used when susceptibility artifacts are too strong for EPI-DWI.²⁶ In addition, view angle tilting could be used with EPI to reduce geometric distortions caused by B_0 inhomogeneity.²⁷

This work was motivated by the possibility of correcting MRI artifacts induced by orthodontic appliances using permanent magnets with a strong coercivity (Rollins NK, presentation at Philips Pediatric MRI users meeting, January

2013). The measurements in this work were only performed at 1.5 T mainly because this is the most common MRI field strength today. The induced magnetic moment in orthodontic appliances is weaker at 1.5 T than that at 3 T or higher field strengths. Consequently, a field correction device will only need weaker permanent magnets for artifact correction in a weaker B_0 field, and this situation is more favorable than that at a higher B_0 field from a safety viewpoint.

There are many types of stainless steel alloys with wide ranges of composition and phase associated with different crystalline structures.²⁸ Their magnetic properties vary considerably from being nonmagnetic (austenitic grades) to highly magnetic (ferritic or martensitic grades).²⁸ One single bracket

TABLE IX. Total induced m_z at 1.5 T of full length stainless steel arch wires from several vendors.

Brand	Wire type	Wire cross sectional size (in.)	Total induced m_z (10^{-4} A·m ²)
Class 1	Lower wire	0.014 ^a	62
	Lower wire	0.018 ^a	101
	Lower wire	0.016×0.022 ^b	137
	Lower wire	0.018×0.025 ^b	152
3M Unitek	Lower wire	0.018×0.022 ^b	170
	Upper wire	0.016×0.022 ^b	246
	Upper wire	0.018×0.022 ^b	195
Ormco Orthos	Small lower wire	0.016 ^a	126
	Small lower wire	0.017×0.025 ^b	164
	Small upper wire	0.018 ^a	177
	Small upper wire	0.016×0.022 ^b	119

^aDiameter.

^bHeight×width.

TABLE VIII. Induced magnetic moment in molar brackets and bands.

Brand	Position	Number of parts studied	Induced m_z (10^{-4} A·m ²)
Ormco Peerless brackets	Lower 6	2	2.7, 3.0
	Lower 7	2	1.0, 1.4
	Upper 6	2	2.9, 3.4
	Upper 7	2	1.0, 1.2
Ormco band with bracket	Lower molar	2	3.9, 5.1
	Upper molar	2	5.1, 13.0
3M Unitek band with bracket	Lower molar	2	23.3, 42.9
	Upper molar	2	99.3, 166.0

Note: 6 = first molar; 7 = second molar.

may have different types of stainless steels for the mesh, base, and wing,²⁹ assembled together with silver based brazing alloys. Different mechanical properties may be desired for different parts of orthodontic appliances. While stand-alone brackets need to be rigid, molar bands need certain malleability so they can perfectly fit on the teeth. Consequently, vendors employ different stainless steels for different parts. As technologies advance, the materials used for orthodontic appliances also change with time, offering improved mechanical and anticorrosion performances. For these reasons, it should not be too surprising that various parts in this study have quite different magnetic moments. In most cases, information on the exact alloy composition of orthodontic appliances is not readily available. From a medical physics view point, this information is not needed for the correction of the MRI artifacts. In a clinical setting, optimal correction of the artifacts will depend on a calibration measurement, based on which a field correction device that best matches the braces can be used. The current study allows us to estimate the range of magnetic moments that we may need to deal with in clinical practice.

A limitation of the study is that the measurements were far from exhaustive to cover all available parts of available orthodontic appliances. Many vendors supply components of orthodontic appliances, and each vendor also offers different models. New designs of brackets with improved functionality continue to emerge. In a patient undergoing brain MRI, the vendor supplying parts of the braces is usually unknown, and the orthodontist could have used components from different vendors in one patient. Our study suggested that a wide range of total induced total magnetic moment could be found in a patient. Another limitation of the study is that dental restorations or prosthesis uses permanent dental implants, which sometimes contain ferromagnetic components. These implants are not addressed in this work.

Our results showed that at 1.5 T, the longitudinal component of the induced magnetic moment is dominating, and the induced magnetic moment is insensitive to the orientation. This means that even if the patient's head tilting angle may change, the induced magnetic moment from each part of the orthodontic appliances will remain approximately constant although the B_0 field distribution will change inside the brain. The results of this study will be valuable in guiding the effort in correcting MRI artifacts caused by ferromagnetic orthodontic appliances.

5. CONCLUSIONS

The induced magnetic moment of stainless steel orthodontic appliances at 1.5 T was studied. The induced magnetic moment was dominated by the longitudinal component (along the direction of the B_0 field). On average, the transverse component was less than 5% of that of the longitudinal component for orthodontic brackets. The induced longitudinal magnetic moment was insensitive to the orientation relative to the B_0 field, with a coefficient of variation of 0.6% for brackets. Orthodontic brackets collectively contributed most to the total magnetic moment in dental braces. There was a factor of 1.5 of

variability in induced magnetic moment among brackets from different vendors.

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^{a)}Author to whom correspondence should be addressed. Electronic mail: jerry.wang@childrens.com; Telephone: 214-456-1479; Fax: 214-456-6015.

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