Effects of magnetic fields from electric toothbrushes on fluoride- and oral bacteria-induced corrosion of orthodontic metallic wires

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INTRODUCTION

Fluoride-containing mouthwashes and toothpastes for home use, and fluoride treatments in the dental clinic, are effective methods for preventing dental caries in dental patients with fixed appliances, especially those with complicated morphologies10. However, fluoride-containing environments also reduce the corrosion resistance of pure titanium and titanium alloys through the breakage of their protective surface oxide layers25-28, and can corrode stainless steel dental appliances29. The corrosion resistance of titanium depends on the fluoride concentration and the pH value30.

Microbial activity on the surface of metallic materials can affect the kinetics of cathodic and/or anodic reactions and can considerably modify the chemistry of any protective layers, leading to acceleration of corrosion of dental metallic appliances21-23. The process of metal corrosion in dental appliances is generally studied by evaluating changes in the potential/current density and color properties (indirect evidence) and the surface roughness of the metal and the elements eluted to the immersed solutions (direct evidence). The surface of intact orthodontic wires, however, is not always perfectly smooth and it may be difficult to judge whether small amounts of corrosion have taken place on appliances based solely on observation of their surface quality.

Electric toothbrushes are widely used because of their convenience. Previous reports in this area have indicated that magnetic fields (MFs) from electric toothbrushes can induce an alternating electric current (AC) in metallic dental appliances and teeth31,32. Some studies have suggested that metallic corrosion occurs in the presence of an electromagnetic field-induced AC33,34. Our previous study indicated that MFs from electric toothbrushes promoted the corrosion of orthodontic stainless steel (SUS) but not titanium appliances in artificial saliva through an induced current35.

In our current study, we investigated the additive and synergistic effects of MF exposure from electric toothbrushes on fluoride- and microbiologically-induced corrosion of orthodontic wires.

MATERIALS AND METHODS

Materials

Orthodontic wires made of SUS (SUS304, Suzuki stainless wire, Mitsuba Ortho Supply, Tokyo, Japan) and of nickel titanium (Ni-Ti; Sentalloy, Tomy International, Tokyo, Japan) were prepared with a cross-sectional size of approximately 0.43×0.64 mm and length of 3.0 cm.

For the fluoride experiment with MFs, Fusayama-Meyer artificial saliva (AS) solution36-38, and a solution containing 450 and 900 ppm of fluoride (Miranol powder [NaF], Bee Brand Medico Dental, Osaka, Japan) dissolved in distilled water as fluoride mouthwash were used as the immersion solutions, taking into consideration fluoride usage through mouthwashes and toothpastes, and the precipitation of calcium fluoride when NaF was dissolved in AS. For the oral bacteria experiment with MF, the immersion solution was brain heart infusion medium (BHI; Beckton, Dickinson and

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Company, Detroit, MI, USA) with or without indigenous oral bacteria *S. mutans* (ATCC25175) or *S. sanguinis* (ATCC49298).

Five different sets of experimental conditions were used to simulate the exposure of orthodontic appliances to the electric toothbrush MF using five Philips Sonicare HX9340/02 electric toothbrushes (Philips Oral Healthcare, Bothell, WA, USA) on a turntable (battery type turntable, MM Kobo, Shizuoka, Japan) rotated at $5 \times 10^{-2}$ Hz (Fig. 1)\(^{14}\).

**Measurement of the electric toothbrush MF and induced current in orthodontic wires in each solution**

The MFs generated by the electric toothbrushes and their frequencies (1 to 2,000 Hz) were detected and evaluated using a spectrum analyzer (SPECTRAN NF-5035, Aaronia AB, Euscheid, Germany)\(^{10,11,14}\). We measured MFs of turntable turned on with electric toothbrushes turned off at the measurement position. Because of the weakness of electric motor power of turntable and long distance (approx. 20 cm) between the turntable and the measurement position, we confirmed no differences of MFs from turntables between turned on and turned off, which were exhibited almost 0 values.

The electric currents induced in the orthodontic wires (predominantly AC induced by MFs from electric motor of the electric toothbrush) were estimated using a digital multimeter (7351 A/E, ADC, Tokyo, Japan) in AC+DC mode \(voltage=(ACV^2+DCV^2)^{1/2}\), and current \(=(ACI^2+DCI^2)^{1/2}\)\(^{10,11,14}\). We checked electric toothbrush-induced electric current in orthodontic wires by estimation with AC, AC+DC and DC mode of a digital multimeter in preliminary study, which indicated that AC and AC+DC data were almost same, and DC data was almost zero values. Values of DC mode should be negligible, however we decided to estimate the induced current in wires by AC+DC mode of a digital multimeter considering the possibility of DC induced by electric toothbrush-derived MFs from electronic circuit system besides electric motor of the electric toothbrush (Fig. 1, Table 1)\(^{10,11,14}\). In preliminary experiment, we checked the most close distance between the electric toothbrush and the appliance on tooth surface, which was identified 2.0–3.0 cm as the distance between frontal body surface of electric toothbrush and the metallic appliance on the anterior tooth surface when brushing molars with an electric toothbrush. Therefore, the induced electric current values were estimated at a distance of 3.0 cm between the front of the toothbrush and the wire, which was immersed in AS, BHI, fluoride solution or oral bacteria solution in a plastic culture dish.

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**Fig. 1**  Schematic representation and time schedule of experiment.
Table 1  Electric voltage (mV) and current (mA) induced by electric toothbrushes in orthodontic wires immersed in each solution

A. Fluoride environment

| Artificial saliva | Fluoride solution |
|-------------------|-------------------|
|                   | 450 ppm | 900 ppm |
| MF                | −       | +       | −       | +       | −       | +       |
| SUS               |         |         |         |         |         |         |
| Induced voltage   | 0.02a,A  | 0.55b,A | 0.02a,A  | 0.55b,A | 0.02a,A  | 0.54b,A |
|                   | (0.007)  | (0.072) | (0.008)  | (0.072) | (0.006)  | (0.071) |
| Induced current   | 0.02a,A  | 0.52b,A | 0.02a,A  | 0.53b,A | 0.03a,A  | 0.55b,A |
|                   | (0.007)  | (0.087) | (0.007)  | (0.087) | (0.006)  | (0.086) |
| Ni-Ti             |         |         |         |         |         |         |
| Induced voltage   | 0.02a,A  | 0.58b,A | 0.03a,A  | 0.56b,A | 0.02a,A  | 0.54b,A |
|                   | (0.005)  | (0.062) | (0.006)  | (0.058) | (0.007)  | (0.065) |
| Induced current   | 0.02a,A  | 1.18b,B | 0.03a,A  | 1.08b,B | 0.02a,A  | 1.1b,B  |
|                   | (0.008)  | (0.108) | (0.006)  | (0.101) | (0.007)  | (0.098) |

B. Oral bacteria environment

| BHI medium | Oral bacteria |
|------------|---------------|
| S. mutans | S. sanguinis |
| MF         | −       | +       | −       | +       | −       | +       |
| SUS        |         |         |         |         |         |         |
| Induced voltage | 0.02a,A  | 0.54b,A | 0.02a,A  | 0.52b,A | 0.02a,A  | 0.53b,A |
|            | (0.008)  | (0.065) | (0.007)  | (0.044) | (0.008)  | (0.049) |
| Induced current | 0.02a,A  | 0.55b,A | 0.02a,A  | 0.50b,A | 0.02a,A  | 0.54b,A |
|            | (0.007)  | (0.070) | (0.006)  | (0.067) | (0.007)  | (0.083) |
| Ni-Ti      |         |         |         |         |         |         |
| Induced voltage | 0.02a,A  | 0.56b,A | 0.02a,A  | 0.53b,A | 0.02a,A  | 0.56b,A |
|            | (0.006)  | (0.067) | (0.005)  | (0.061) | (0.008)  | (0.071) |
| Induced current | 0.02a,A  | 1.22b,B | 0.02a,A  | 1.18b,B | 0.02a,A  | 1.25b,B |
|            | (0.007)  | (0.098) | (0.008)  | (0.121) | (0.008)  | (0.098) |

n=6 for each experimental condition. Values are mean and (SD). MF: magnetic field. Different superscript small and capital letters denote statistically significant differences (p<0.05) within the electric voltage or current of each wire, and the electric voltage or current of each experimental condition, respectively.

Exposure of the orthodontic wires to MFs in a fluoride-containing environment
Orthodontic wires were immersed in 8 mL of a fluoride-containing solution in a 15 mL plastic tube, and were exposed to an electric toothbrush MF for 24 min/day. A total exposure time of 120 min was achieved for each toothbrush (24 min each) following 5 days of exposure to each wire (Fig. 1).

Culture of orthodontic wires with indigenous oral bacteria with MF exposure
Wires were cultured with S. mutans or S. sanguinis in 8 mL of BHI medium in a 15 mL plastic tube and incubated at 37°C in 5% CO₂ in air without shaking. A saturated culture of S. mutans or S. sanguinis with an optical density (OD) of 0.6–1.0 at 660 nm was diluted 40-fold with BHI medium and incubated from day 0 to day 4 (Fig. 1). Orthodontic wires were cultured with each species of oral bacteria for 3 h on day 0 and for 24 h on days 1–4. Supernatants were collected at days 0–4 to evaluate metallic elution, and the wires were collected at day 4 to evaluate surface roughness (Fig. 1). Chronologic estimation of the OD of each bacterial culture seeded with an initial OD of 0.01 with S. mutans and of 0.001 with S. sanguinis revealed significant elevation from 6 h in S. mutans and 2 h in S. sanguinis, and reached confluence at 8.5 h in S. mutans (OD=0.75–0.8) and at 6.5 h in S. sanguinis (OD=0.53–0.55). After reaching confluence, the growth curves of S. mutans and S. sanguinis exhibited a stationary phase, followed by a death phase after culture for an additional 72 h. The influence of 24 min of MF exposure on bacterial growth was estimated by measuring the OD at 660 nm at 4.5 and 24 h using a Mini Photo 518R (Taitec, Tokyo, Japan) under 5% CO₂ conditions.

Measurement of pH and metallic elution of each solution after immersion or co-culture of orthodontic wires with indigenous oral bacteria under MF exposure
The immersion solutions were collected following each
Table 2  pH changes in the immersion solution of the wires, with or without magnetic field exposure from electric toothbrushes

A. Fluoride environment

|                  | Artificial saliva | Fluoride solution |
|------------------|-------------------|-------------------|
|                  | MF − | + | MF − | + | MF − | + | MF − | + |
| SUS              | 4.9±A | (0.12) | 5.0±A | (0.11) | 5.5±A | (0.12) | 5.4±A | (0.09) | 5.4±A | (0.11) |
| Ni-Ti            | 4.9±A | (0.09) | 5.0±A | (0.12) | 5.5±A | (0.08) | 5.4±A | (0.12) | 5.4±A | (0.09) |
| No wire          | 5.3±B | (0.09) | 5.3±A | (0.08) | 5.5±A | (0.11) | 5.5±A | (0.13) | 5.5±A | (0.10) |

B. Oral bacteria environment

|                  | BHI medium | S. mutans | S. sanguinis |
|------------------|------------|-----------|-------------|
|                  | MF − | + | MF − | + | MF − | + | MF − | + |
| SUS              | 5.8±A | (0.12) | 5.9±A | (0.09) | 5.4±A | (0.11) | 5.4±A | (0.09) | 5.4±A | (0.10) |
| Ni-Ti            | 6.4±B | (0.10) | 6.5±B | (0.14) | 5.7±B | (0.12) | 5.8±B | (0.11) | 5.9±B | (0.11) |
| No wire          | 7.5±C | (0.17) | 7.4±C | (0.11) | 6.7±C | (0.13) | 6.6±C | (0.15) | 6.9±C | (0.14) |

n=6 for each experimental condition. Values are mean and (SD). MF: magnetic field. Different superscript small and capital letters denote statistically significant differences (p<0.05) within each wire and each experimental condition, respectively.

immersion or co-culture experiment with an orthodontic wire, and their pH values were measured with a pH meter (F-12, Horiba, Kyoto, Japan, Table 2). After incubation, each supernatant at days 0–4 from the same tubes was collected and combined without the wire or bacteria to measure the metallic elution of Cr, Fe, Ni and Ti from the orthodontic wires using an inductively coupled plasma-optical emission spectrometer (ICP-OES; Thermo Fisher Scientific ICP-OES model iCAP6300DUO, Waltham, MA, USA, Fig. 1)14,16). The ICP-OES instrument was optimized before measurement using standard solutions of Cr, Fe, Ni and Ti for atomic absorption spectrometry (Kanto Chemical, Tokyo, Japan), and operated according to the manufacturer’s instructions. The ICP-OES was used with the following parameters: FR power, 1.15 kW; frequency, 27.12 MHz; demountable quartz torch, Ar/Ar/Ar; plasma gas (Ar) flow, 16.5 Lmin⁻¹; auxiliary gas (Ar) flow, 0.5 Lmin⁻¹; nebulizer gas (Ar) flow, 0.7 Lmin⁻¹; nebulizer pressure, 0.15 MPa; Scott-type glass spray chamber (cylinder chamber, Fisher Scientific, MA, USA); sample pump flow rate, 1.8 mLmin⁻¹; integration time, 45 s; replicates, 5; and wavelength range of monochromator, 166–847 nm. Standard curves of BHI medium with or without Cr, Fe, Ni, Sn and Ti were created, and then the detection limits (3.3δ/slope) and determination limits (10√2δ/slope) were obtained according to ISO 118843 (Table 3). The elution values of the metallic ions in the medium were shown as concentrations (ppb/ppm), so that these values could be converted to the eluted metal weight (µg) for easier understanding (Tables 3–5). Selected metal ions were measured at wavelengths of 205.552 nm for Cr, 261.187 nm for Fe, 231.604 nm for Ni and 308.802 nm for Ti from the results of each standard curve (Table 3). The metallic elution was displayed as a mean value (≥determination limit), +(detection values<measured values<determination limit) or –(<detection limit)14,16) (Tables 3A–D). All reagents used in this experiment were analytical and spectral purity grade.

Detection of the surface roughness of the orthodontic wires by three-dimensional (3D) laser confocal microscopy

The surface roughness of the wires in each combination was measured using a 3D laser confocal microscope (LEXT OLS4000, Olympus, Tokyo, Japan) and estimated as Ra (the arithmetic average of the absolute value)17), and Rz (the highest peaks and lowest valleys over the entire sampling length) using the LexT software package (Olympus) on a workstation computer (MB-P5300X-WS, Mouse Computer, Tokyo, Japan)14,16). The surface roughness was measured on the center of the labial surface of the wire (the 500 µm mesiodistal line of the
Table 3 Detection and determination limits (µg) at different detection wavelengths (nm) of different elements in the immersion solutions, as determined by ICP-OES

A. Artificial saliva

| Element | Detection wavelength | Detection limit | Determination limit |
|---------|----------------------|-----------------|--------------------|
| Cr      | 205.552              | 0.012           | 0.048              |
| Fe      | 239.562              | 0.016           | 0.070              |
| Ni      | 216.556              | 0.027           | 0.119              |
| Ti      | 308.802              | 0.007           | 0.025              |

B. Fluoride solution (450 ppm)

| Element | Detection wavelength | Detection limit | Determination limit |
|---------|----------------------|-----------------|--------------------|
| Cr      | 205.552              | 0.012           | 0.051              |
| Fe      | 259.940              | 0.023           | 0.097              |
| Ni      | 231.604              | 0.014           | 0.061              |
| Ti      | 308.802              | 0.015           | 0.064              |

C. Fluoride solution (900 ppm)

| Element | Detection wavelength | Detection limit | Determination limit |
|---------|----------------------|-----------------|--------------------|
| Cr      | 205.552              | 0.016           | 0.068              |
| Fe      | 259.940              | 0.054           | 0.232              |
| Ni      | 231.604              | 0.023           | 0.112              |
| Ti      | 308.802              | 0.018           | 0.079              |

D. BHI medium

| Element | Detection wavelength | Detection limit | Determination limit |
|---------|----------------------|-----------------|--------------------|
| Cr      | 205.552              | 0.014           | 0.062              |
| Fe      | 259.940              | 0.192           | 0.824              |
| Ni      | 231.604              | 0.021           | 0.093              |
| Ti      | 308.802              | 0.018           | 0.066              |

wire)\textsuperscript{12,14}.

Experimental conditions, data and statistical analyses

All experiments described in the current study were performed in our laboratory, which was maintained at a temperature of 22±1°C. In total, eight sets of experimental data were obtained, and the maximum and minimum data sets were removed to leave only six experimental data sets. These six data sets were then averaged to give the means values±standard deviation (SD). These data were then analyzed using the Mann-Whitney $U$ test to determine whether any of the differences were statistically significant.

RESULTS

Electric currents induced in orthodontic wires by low frequency MFs from electric toothbrushes

The orthodontic wires were exposed to MFs from all sides of the electric toothbrush rotated on a turntable at $5\times10^{-2}$Hz (Fig. 1). The MF profiles from different sides of the toothbrush were similar, and the fields were ranked as right$>$left$>$back$>$front side (Fig. 2).

The currents induced in the wires at a distance of 3 cm from the surface of the toothbrush with the wire immersed in a plastic tube containing AS, a distilled water solution containing 450 or 900 ppm of fluoride, or BHI medium with/without oral bacteria are shown in Table 1. The voltage and current for the SUS or Ni-Ti wires when facing the electric toothbrush in a fixed position are also shown in Table 1. In any combination, the MF-induced electric current was greater in the Ni-Ti wires than in the SUS wires (Table 1).

Optical density change in oral bacteria cultured with orthodontic wires under MF exposure

The OD of each bacterial culture with/without wires revealed significant elevation from 6 and 2 h, and
Fig. 2 Low frequency magnetic fields produced by the electric toothbrush.
The magnetic field (1–2,000 Hz) produced by the Sonicare HX9340/02 was measured at a distance of 3 cm between the electric toothbrush and the front/right/left/back side of the appliance with a spectrum analyzer.

Fig. 3 Optical density (OD) of oral bacteria incubated with orthodontic wires for 4.5 and 24 h under magnetic field exposure.
A: S. mutans. B: S. sanguinis. Left: Incubation for 4.5 h. Right: Incubation for 24 h. No significant differences were observed within each wire group or within each experimental condition.

Fe was detected in all solutions with SUS wires in the fluoride group with/without MF exposure (Table 4A). The amount of Fe eluted from the SUS wires in the fluoride solution was similar to the amount eluted from the SUS wires with MF exposure in AS (Table 4A). Elution of Cr and Ni from SUS wires was detected in AS with MF exposure and any group in the fluoride solution. In contrast, Ni and Ti elution from Ni-Ti wires was detected in the fluoride groups, and these elution volumes were dose-dependent, i.e. 900 ppm F>450 ppm F (Table 4B). MF exposure did not promote metallic elution from Ni-Ti wires in AS and fluoride solutions, or from SUS wires in fluoride solutions (Table 4).

Metallic elution of each component of the wires to the medium was also evaluated. Although the detection and determination limits of Fe were high compared with those of the other components, only Fe elution from SUS wires was detected as a measured value (determination limit) when co-cultured with S. sanguinis (Table 5A). In BHI medium with MF exposure, Cr, Fe, and Ni elution was detected only at levels beyond the determination limits. This was also the case with Cr, Fe and Ni elution from SUS wires with S. mutans, and Cr and Ni elution with S. sanguinis with/without MF exposure (Table 5A). No elution of Ni and Ti from Ni-Ti wires was detected in any combination (Table 5B).

Surface roughness of orthodontic wires in the fluoride and oral bacteria solutions under MF exposure
The 3D laser confocal micrographs of the surface of the wires are shown in Figs. 4A–C. The measured and
calculated surface roughness of the wires, as well as the Ra and Rz values in the fluoride and oral bacteria environments, are shown in Tables 6 and 7.

These results reveal that the fluoride solution made the surface of the SUS and Ni-Ti wires uneven (Tables 6A, B). The surface roughness of both wires was dose-dependently related to fluoride concentration. MF exposure made the surface of the SUS wires uneven in AS, but not in the fluoride solutions. MF exposure had no discernible impact on the surface of the Ni-Ti wires.

Table 4  Elution of each element (µg) from wires in a fluoride environment
A. SUS wires

| Artificial saliva | Fluoride solution |
|------------------|-------------------|
|                  | 450 ppm | 900 ppm |
| MF               | –  | +  | –  | +  | –  | +  |
| Cr               | –  | +  | +  | +  | +  | +  |
| Ni               | –  | +  | +  | +  | +  | +  |
| Fe               | 0.10\(^a\) | 0.69\(^b\) | 0.65\(^b\) | 0.69\(^b\) | 0.71\(^b\) | 0.70\(^b\) |
| (0.014)          | (0.080) | (0.064) | (0.070) | (0.063) | (0.061) |

B. Ni-Ti wires

| Artificial saliva | Fluoride solution |
|------------------|-------------------|
|                  | 450 ppm | 900 ppm |
| MF               | –  | +  | –  | +  | –  | +  |
| Ni               | –  | –  | –  | –  | –  | –  |
| Ti               | –  | –  | –  | –  | –  | –  |

\(n=6\) for each experimental condition. Values are mean and (SD). MF: magnetic field. +: detection values≤ measured values< determination limit, and –: measured values< detection limit. Different superscript small letters denote statistically significant differences \((p<0.05)\) within each element.

Table 5  Elution of each element (µg) from wires co-cultured with oral bacteria
A. SUS wires

| BHI medium | Oral bacteria |
|------------|---------------|
|            | S. mutans     | S. sanguinis  |
| MF         | –  | +  | –  | +  | –  | +  |
| Cr         | –  | +  | +  | +  | +  | +  |
| Fe         | –  | +  | +  | +  | 0.88\(^a\) | 0.87\(^a\) |
| (0.016)    | (0.013) | (0.089) | (0.049) |
| Ni         | –  | +  | –  | –  | –  | –  |
| Ti         | –  | –  | –  | –  | –  | –  |

B. Ni-Ti wires

| BHI medium | Oral bacteria |
|------------|---------------|
|            | S. mutans     | S. sanguinis  |
| MF         | –  | +  | –  | +  | –  | +  |
| Ni         | –  | –  | –  | –  | –  | –  |
| Ti         | –  | –  | –  | –  | –  | –  |

\(n=6\) for each experimental condition. Values are mean and (SD). MF: magnetic field. +: detection values≤ measured values< determination limit, and –: measured values< detection limit. Different superscript small letters denote statistically significant differences \((p<0.05)\) within each element.
in either the AS or fluoride-containing solutions (Tables 6A, B). It was clear from the micrographs that the surface of the intact wires was not entirely smooth, and it was therefore difficult to make any conclusions about changes in the surface resulting from exposure to the fluoride-containing solution and the MF (Figs. 4A, B).

Oral bacteria also made the surface of the SUS wires uneven, but did not affect the Ni-Ti wires (Tables 7A, B). The rank order of surface roughness of SUS wires was: *S. sanguinis* with/without MF > *S. mutans* with/without MF > no bacteria with MF > no bacteria and no MF > intact product (Table 7A). The surface of the intact wires was not smooth; however, obvious surface changes in the SUS wires caused by *S. sanguinis* and *S. mutans* were observed as numerous corrosion pits, supporting evaluation of surface roughness as Ra and Rz (Figs. 4A, C).

**DISCUSSION**

Intraoral aging of orthodontic materials includes plasticization of polymeric adhesives and increased porosity and roughness of metallic alloys, which disturb smooth treatment progress and cause loss of time and money as well as emotional distress for patients and clinicians21,22. Most orthodontic wires used in dental appliances are made from SUS and titanium alloys, especially SUS304 and Ni-Ti. Given that the biocompatibility of these devices can be related to their corrosion properties, there have been many reports in the literature concerning the corrosion behavior of orthodontic alloys, with particular emphasis on the...
corrosion properties of Ni-Ti wires in fluoride-containing environments\textsuperscript{23-25} at different temperatures\textsuperscript{26}, and under bending stress\textsuperscript{27}, galvanic corrosion\textsuperscript{1,28,29} and their corrosion phenomena in the oral environment\textsuperscript{30-32}.

A previous study in this area also demonstrated that an alternating electric current can be induced in orthodontic appliances by the electromagnetic fields generated by electric toothbrushes\textsuperscript{10}. Given that the induced currents in appliances resulting from the MFs of electric toothbrushes are different from galvanic...

corrosion (µm) of wires in fluoride environment

|       | Non | Artificial saliva | Fluoride solution | Fluoride solution |
|-------|-----|-------------------|-------------------|-------------------|
|       |     |                   | 450 ppm | 900 ppm |
| MF    |     |                   |         |         |
| Ra    | 0.01\textsuperscript{a} | 0.02\textsuperscript{a} | 0.07\textsuperscript{b} | 0.16\textsuperscript{c} | 0.18\textsuperscript{c} | 0.26\textsuperscript{d} | 0.25\textsuperscript{d} |
|       | (0.008) | (0.016) | (0.012) | (0.042) | (0.046) | (0.044) | (0.063) |
| Rz    | 0.12\textsuperscript{a} | 0.15\textsuperscript{a} | 0.48\textsuperscript{b} | 1.15\textsuperscript{c} | 1.16\textsuperscript{c} | 1.75\textsuperscript{d} | 1.81\textsuperscript{d} |
|       | (0.010) | (0.033) | (0.018) | (0.122) | (0.135) | (0.164) | (0.138) |

B. Ni-Ti wires

|       | Non | Artificial saliva | Fluoride solution | Fluoride solution |
|-------|-----|-------------------|-------------------|-------------------|
|       |     |                   | 450 ppm | 900 ppm |
| MF    |     |                   |         |         |
| Ra    | 0.20\textsuperscript{a} | 0.20\textsuperscript{a} | 0.20\textsuperscript{a} | 0.26\textsuperscript{b} | 0.25\textsuperscript{b} | 0.32\textsuperscript{c} | 0.30\textsuperscript{c} |
|       | (0.012) | (0.019) | (0.016) | (0.035) | (0.031) | (0.047) | (0.038) |
| Rz    | 1.38\textsuperscript{a} | 1.40\textsuperscript{a} | 1.42\textsuperscript{a} | 2.39\textsuperscript{b} | 2.48\textsuperscript{b} | 2.83\textsuperscript{c} | 2.72\textsuperscript{c} |
|       | (0.043) | (0.034) | (0.063) | (0.226) | (0.174) | (0.121) | (0.147) |

n=6 for each experimental condition. Values are mean and (SD). MF: magnetic field. Different superscript small letters denote statistically significant differences (p<0.05) within each measurement item.

Table 7  Surface roughness (µm) of wires co-cultured with oral bacteria

A. SUS wires

|       | Non | BHI medium | Oral bacteria | Oral bacteria |
|-------|-----|------------|---------------|---------------|
|       |     |            | S. mutans     | S. sanguinis  |
| MF    |     |            |               |               |
| Ra    | 0.01\textsuperscript{a} | 0.02\textsuperscript{a} | 0.04\textsuperscript{b} | 0.05\textsuperscript{b} | 0.05\textsuperscript{b} | 0.07\textsuperscript{c} | 0.08\textsuperscript{c} |
|       | (0.008) | (0.014) | (0.009) | (0.008) | (0.009) | (0.009) | (0.012) |
| Rz    | 0.12\textsuperscript{a} | 0.13\textsuperscript{a} | 0.27\textsuperscript{b} | 0.25\textsuperscript{b} | 0.29\textsuperscript{b} | 0.35\textsuperscript{c} | 0.36\textsuperscript{c} |
|       | (0.010) | (0.019) | (0.046) | (0.069) | (0.039) | (0.043) | (0.042) |

B. Ni-Ti wires

|       | Non | BHI medium | Oral bacteria | Oral bacteria |
|-------|-----|------------|---------------|---------------|
|       |     |            | S. mutans     | S. sanguinis  |
| MF    |     |            |               |               |
| Ra    | 0.20\textsuperscript{a} | 0.20\textsuperscript{a} | 0.20\textsuperscript{a} | 0.2\textsuperscript{a} | 0.21\textsuperscript{b} | 0.21\textsuperscript{b} | 0.21\textsuperscript{c} |
|       | (0.012) | (0.020) | (0.012) | (0.013) | (0.019) | (0.018) | (0.016) |
| Rz    | 1.38\textsuperscript{a} | 1.39\textsuperscript{a} | 1.41\textsuperscript{a} | 1.40\textsuperscript{b} | 1.39\textsuperscript{c} | 1.41\textsuperscript{b} | 1.42\textsuperscript{d} |
|       | (0.043) | (0.046) | (0.045) | (0.094) | (0.049) | (0.063) | (0.071) |

n=6 for each experimental condition. Values are mean and (SD). MF: magnetic field. Different superscript small letters denote statistically significant differences (p<0.05) within each measurement item.
currents in terms of their properties, such as alternating current (AC) vs direct current (DC), there have been several reports concerning metallic corrosion caused by electromagnetic field-induced AC. We have also previously reported metallic elution from SUS appliances in AS following exposure of appliances to MFs from electric toothbrushes.

MFs from the different sides of the toothbrushes produced similar profiles in all five electric toothbrushes of same product (Sonicare HX9340/02, Fig. 2). As we previously checked the peaks at the frequencies of MFs of various electric toothbrushes, the peak of MF was different in each electric toothbrush. Then, wave form of MFs should be peculiar to each instrument. The presence of peaks at the particular frequencies of each electric toothbrush must be due to each motor system of electric toothbrush, however we could not obtain the evidence of its reason for the detail. Induced currents were detected in the wires in the AS, fluoride, and oral bacteria solutions exposed to the MFs (Table 1). The pattern of MF-induced voltages and currents in SUS and Ni-Ti wires in the AS, fluoride and oral bacteria solutions were similar, although the induced current in the SUS wire was lower than that of the Ni-Ti wire. This finding suggests that induced current is dependent on the material (i.e. electrical resistivity values of SUS304: 72 Ωm and Ni-Ti: 80–100 Ωm), rather than on the environment.

The use of fluoride-containing products, such as toothpastes, gels, mouthwashes and composite resins for the bonding of appliances to the tooth surface, has become common in clinical orthodontics to achieve good levels of oral hygiene. Although titanium alloys show superior corrosion resistance to SUS because of the highly protective TiO2 oxide film on their surface, numerous reports have shown that the corrosion resistance of titanium alloys can be reduced in the presence of fluoride ions.

It was envisaged that the induced currents would promote metallic elution from the SUS and titanium wires in a fluoride-containing environment and destroy the passive film on the metal surface. An eight-fold increase in the concentration of Fe was detected in AS for the SUS wires following MF exposure compared with AS with no MF exposure. In the fluoride-containing environments, however, the level of MF-induced corrosion of Fe, Ni, Cr and Ti in each combination was similar to those with MF exposure (Table 4). The MF-induced level of Fe elution from the SUS wires in the solutions containing 450 and 900 ppm of fluoride was similar to the level of Fe elution in the MF-induced AS group. The level of Ti elution from the Ni-Ti wires in the solutions containing 450 and 900 ppm of fluoride effectively supported the results of previous reports. The pH of AS with MF exposure was lower than those of the fluoride-containing solution with/ without MF exposure; however, these pH values were much higher than the depassivation pH of SUS and Ni-Ti wires, so the pH could not be the cause of this metallic elusion. The fluoride-induced corrosion of the SUS and Ni-Ti wires could be stronger than the current-induced corrosion, and indicated that the corrosion resistance of the titanium alloy to the electric current was greater than that of the SUS wires, and was weaker in a fluoride-containing environment. The results of the metallic elution tests were confirmed by the results of the surface roughness tests (shown as Ra and Rz) using the 3D laser confocal microscope (Fig. 4, Tables 6 and 7). Although the surface roughness properties of titanium wires were not affected by immersion in AS and fluoride solutions following MF exposure, fluoride-induced corrosion was detected not only in the titanium wires, but also in the SUS wires, which was consistent with previous reports.

Given that the surface of the intact wires was not particularly smooth, and that there was little difference in the surface micrographs of each combination in the fluoride environment (Fig. 4B), it was difficult to identify any obvious changes in the surfaces following MF exposure. Despite these difficulties, evaluation of the surface roughness properties (i.e. Ra and Rz) could be evaluated in AS with MF exposure and the fluoride environment, which supported the results of the metallic elution experiments.

These results suggest that the risk of corrosion in titanium appliances in a fluoride-containing environment would not be enhanced by electronic device-derived MFs such as those emanating from electric toothbrushes, although fluoride use could lead to an increase in the risk of corrosion not only in titanium appliances, but also in SUS appliances.

Biofilm creation and MIC (microbial-induced corrosion or biocorrosion) occur in aquatic habitats varying in nutrient content, temperature, stress and pH. The oral environment of humans should be one of the most hospitable for biofilm creation and biofouling. The mechanism of MIC is unclear, but it probably results from a combination of several causes including localized electrical events, such as contact between the biofilm and metal surfaces. We previously reported that MIC caused by oral bacteria, such as S. mutans and S. sanguinis, could occur in SUS materials, but not in titanium materials.

Measurement of the growth of each bacterial culture suggests that neither SUS and Ni-Ti wires themselves, nor MFs, have a toxic effect on bacterial growth (Fig. 3). However, the pH of the medium was lowered by the culture of each bacterial species, each type of wire, and each type of wire with each bacterial species, whereas the pH differences in the fluoride environment were not marked (Table 2). This lower pH in the oral bacteria environment could not have eroded these alloys directly, because no solution reached the depassivation pH. The pH changes observed in the current study could not therefore be related to the observed metallic elution processes in the oral bacteria environment or the fluoride environment. However, the pH of the supernatants of the oral bacteria environment may not always reflect local pH changes between the bacteria/biofilm and the wire surface. Apart from local pH changes, local cathode-anode reactions at the contact surfaces of metal and bacteria have been reported to be one of the causes.
The elution of each metallic component (Fe, Cr, and Ni) into the medium from SUS wires co-cultured with oral bacteria was measured, and the MIC of SUS wires (no bacteria) into the medium from SUS wires co-cultured with MF exposure. Because the BHI medium contained bovine heart extract, an iron-rich tissue, the detection limit and determination limit of Fe were high compared with those of the other metallic elements (Table 3). However, only Fe elution was detected as a measured value (>determination limit) from SUS wires, while Cr and Ni elution was detected at a level lower than the determination limits (Table 5). No elution of Ni and Ti was detected from Ni-Ti wires. Although the eluted components were not described in the table because of their low levels (except for Fe with S. sanguinis with/without MF exposure), MF exposure had no effect on metallic elution in any combination. These findings were identical to those of previous reports and are consistent with the results for oral bacterial growth (Figs. 3A, B)16).

The elution of each metallic component (Fe, Cr, and Ni) into the medium from SUS wires co-cultured with oral bacteria was measured, and the MIC of SUS wires with S. mutans was higher than that of SUS wires with S. mutans with/without MF exposure, and BHI medium (no bacteria) with MF exposure. S. mutans mimicked a microbial fuel cell, resulting in power generation during biofilm formation, which could change the local pH and electric charges36). These results indicate that MIC could be a result of internal electric changes caused by oral bacteria (such as power generation), but not of external electric changes (such as induced currents in wires with MF exposure). The results of the surface roughness tests for each wire were supported by the results of the metallic elution tests (Tables 4–7). In contrast with the metallic elution test, the data for the surface roughness of all combination could be described. In Ni-Ti wires, no differences were observed in any combination. In the SUS wires, corrosion was observed in BHI medium with MF exposure, and in the co-cultures with oral bacteria with/without MF exposure. Although the surface of the intact wires was not smooth, a slight increase in surface roughness, including corrosion pits in the SUS wires, was visible under careful observation, supporting the evaluation of surface roughness in terms of Ra and Rz (Fig. 4). These results support previous reports of MIC and MF-induced corrosion of SUS, and the high resistance of titanium alloys to corrosion16,37,38). Corrosion pits caused by S. mutans and S. sanguinis were also observed on SUS wires (Fig. 4C).

These results suggest that corrosion of SUS appliances mainly occurs in the presence of indigenous oral bacteria (S. mutans and S. sanguinis), which easily create a biofilm on the surface of teeth and appliances, rather than by MF exposure from electric toothbrushes.

We have shown in this study that fluoride- and oral bacteria-containing environments can promote metallic elution from wires made from SUS/Ni-Ti or SUS alloys. We demonstrated that these elution processes are not promoted by the low-frequency magnetic fields induced by electric toothbrushes by contrasting them with metallic elution from SUS appliances in AS without fluoride and BHI medium without oral bacteria. These results suggest that titanium alloys possess strong corrosion resistance to electrical currents but not to a fluoride-containing environment, and that the use of fluoride could lead to an enhanced risk of corrosion, not only in titanium, but also in SUS appliances. Although the use of fluoride-containing products has become common in clinical orthodontics to maintain good oral hygiene33,34), great care should be taken in their general use, especially when oral prostheses and/or appliances made from SUS and titanium alloys are used. The results of this study indicated that corrosion of metallic appliances in the oral region may occur as a result of exposure to oral bacteria and fluoride. We also demonstrated that MFs from electric toothbrushes induced an electric current in metallic appliances, and that MF exposure itself corroded SUS appliances. However, these currents did not promote their metallic elution in the presence of fluoride and/or oral bacteria.

In conclusion, we recommend that usage of fluoride-containing substances should be carefully monitored for patients with metallic appliances in their mouth, and the importance of good oral hygiene should be stressed. The MF from electric toothbrushes should not be considered a serious problem contributing to the corrosion of dental metallic appliances, when compared with the more obvious effects of fluoride usage and oral bacteria in the oral cavity.

CONCLUSIONS

We have examined the possibility that fluoride- and oral bacteria-induced metallic corrosion is promoted by MF exposure from electric toothbrushes via induced currents. The results obtained in this study are as follows:

1. induced an electric current in stainless steel and Ni-Ti wires in fluoride- and oral bacteria-containing environments.
2. did not affect the growth of oral bacteria with/without wires.
3. did not affect the pH of fluoride and oral bacteria solutions with/without wires.
4. did not promote fluoride-induced corrosion of stainless steel and Ni-Ti wires.
5. did not promote oral bacteria-induced corrosion of stainless steel wires.

Based on these results, we suggest that MFs from electric toothbrushes do not pose a serious problem, given the more extensive influence of fluoride usage and oral cavity bacteria in the corrosion of dental metallic appliances. Patients with oral metallic appliances should be advised to be cautious when using fluoride-containing substances, and to maintain good oral hygiene.
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