Original Article

Type of Archwire and Level of Acidity: Effects on the Release of Metal Ions from Orthodontic Appliances

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ABSTRACT

Objective: To examine the effects of three different parameters—pH value, type of archwire, and length of immersion—on release of metal ions from orthodontic appliances.

Materials and Methods: Simulated fixed orthodontic appliances that corresponded to one-half of the maxillary arch were immersed in artificial saliva of different pH values (6.75 $\pm$ 0.15 and 3.5 $\pm$ 0.15) during a 28-day period. Three types of archwires were used: stainless steel (SS), nickel-titanium (NiTi), and thermo NiTi. The quantity of metal ions was determined with the use of a high-resolution mass spectrophotometer (HR-ICP/MS).

Results: The release of six different metal ions was observed: titanium (Ti), chromium (Cr), nickel (Ni), iron (Fe), copper (Cu), and zinc (Zn). Repeated measures statistical analysis of variance (ANOVA) was used. Results showed that (1) the appliances released measurable quantities of all ions examined; (2) the change in pH had a very strong effect (up to 100-fold) on the release of ions; and (3) the release of ions was dependent on wire composition, but it was not proportional to the content of metal in the wire. The largest number of ions was released during the first week of appliance immersion.

Conclusion: Levels of released ions are sufficient to cause delayed allergic reactions. This must be taken into account when type of archwire is selected, especially in patients with hypersensitivity or compromised oral hygiene. (*Angle Orthod.* 2009;79:102–110.)

KEY WORDS: Metal ions; Orthodontic appliances; Level of acidity

INTRODUCTION

Recent improvements in the composition and quality of orthodontic alloys have significantly increased their biocompatibility and stability inside the oral cavity. However, cases of hypersensitivity and toxic reactions have been reported. The oral environment is conducive to biodegradation and corrosion of dental materials caused by constant chemical, mechanical, thermal, microbiological, and enzymatic changes.[1]

Fixed orthodontic appliances usually include brackets, bands, and archwires made of stainless steel (SS) (containing approximately 18% chromium and 8% nickel) or nickel-titanium (where nickel content exceeds 50%). These alloys have to be fully biocompatible and must elicit an appropriate biological response within a host.[2] Biocompatibility testing of dental materials consists of three different phases. In vitro laboratory tests and in vivo tests on animals have been done; however, clinical tests on patients, which are the most relevant, are very complex and could raise ethical concerns.[3]

Electrochemical reactions during which the surface of a metal is deteriorated via ion release are called *corrosion.* Internal corrosive factors are determined by metal composition and structure; external factors depend on biological surroundings (eg, media composition, pH, temperature, strain, illumination).

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Several studies have demonstrated that metal ions from fixed orthodontic appliances, primarily nickel and chromium, can cause allergic reactions.[4–9] Other reports have indicated that 4.5% to 28.5% of the population is nickel hypersensitive, and this condition is more prevalent among females.[10–13] This might be so because women could have been sensitized by wearing jewelry that contains nickel.[1,14,15] Besides allergic reactions, metal ions released from orthodontic appliances could have carcinogenic, mutagenic, and cytotoxic effects.[16–19]

The purpose of this study was to determine the types and quantities of metal ions released from three types of archwires of different composition and mechanical properties (nickel-titanium [NiTi], thermo NiTi, and SS) in solutions of different pH values (to simulate saliva and conditions in the presence of dental plaque). Furthermore, the effects of change in pH and time of exposure on release of metal ions from these alloys were evaluated.

MATERIALS AND METHODS

This study used simulated fixed orthodontic appliances, each of which represented half of the maxillary arch. Each appliance consisted of five brackets, from second premolar to central incisor, a molar band with a buccal tube, and an archwire tied with metal ligatures. The 0.016 $\times$ 0.022-inch archwires were 6 cm long and were shaped to an ideal arch form. All materials used were made by Dentaurum (Ispringen, Germany).

To simulate changing conditions in the oral cavity, artificial saliva of different pH values was used; selection was based on average pH in the oral cavity (6.75) and lowest pH (3.5) found under mature dental plaque.[20] Artificial saliva was prepared in keeping with the formula of Barret, Bishara, and Quinn,[1] which is a modification of that used by Gjerdet and Hero.[21] The pH values were adjusted with the use of 10 M sodium hydroxide (NaOH), or lactic acid, which is a product of bacterial metabolism in dental plaque.

A total of 18 simulated fixed appliances were used: Nine of these (three containing NiTi archwire, three containing thermo NiTi archwire, and three containing SS archwire) were immersed in the first solution in polyethylene bottles; the other nine were dipped into the second solution, also in polyethylene bottles. All bottles and laboratory equipment were kept in a digester for 12 hours, were immersed into 65% nitric acid (HNO_3) diluted in water (1:4), and were washed in deionized water and dried. Upon cleansing, the appliances were distributed in polyethylene bottles. The 18 polyethylene bottles each contained 50 mL of artificial saliva—9 at the pH of 6.75 $\pm$ 0.15, and 9 at the pH of 3.5 $\pm$ 0.15. Bottles were stored at 37°C, and samples were collected after 1, 7, 14, and 28 days. To avoid saturation with released ions, artificial saliva solutions were replaced after each sample collection. At the end of 37°C incubation, one drop of 65% HNO_3 was added into each sample with a pH of 6.75 $\pm$ 0.15, to keep the released ions stable in the solution.

A total of 72 solution samples (from 18 appliances with four solution changes) were collected and analyzed. Furthermore, three samples from each of the two solutions (pH 6.75 $\pm$ 0.15 and pH 3.5 $\pm$ 0.15) were used as a blind test (“0” sample) to calibrate the spectrophotometer. The samples were analyzed for the contents of ions of titanium (Ti), nickel (Ni), chromium (Cr), and iron (Fe), as well as copper (Cu) and zinc (Zn) ions contained in the brackets’ silver solder. A high-resolution inductively coupled plasma mass spectrometry (HR-ICP/MS) device (Esolderent 2; Finnigan MAT, San Jose, Calif) was used for the sample analysis conducted at the Centre for Trace Analysis, University of Southern Mississippi, in Hattiesburg, Mississippi. This device allows measurement of extremely low concentrations of released ions. Detection limits (threshold of analysis) of the ICP unit were as follows: $<$100 ppq (parts per 10^{15}) for Ti, Cr, Fe, and Cu, and $<$500 ppq for Ni and Zn. For statistical analysis, a repeated measures analysis of variance (ANOVA) was used to test the effects of two independent variables (wire type and pH) and one dependent (time/length of immersion) variable.

RESULTS

Results of the analysis of concentration of released ions of Ti, Cr, Ni, Fe, Cu, and Zn are shown in Figures 1 and 2. Each graph displays the quantity of released metal ions during each time period (bar graphs) and the total quantity of metal ions released from the beginning of the experiment (line graphs). The largest ion release among all observed elements, for all types of appliances and for both solutions, was noticed in the first two observed intervals (ie, in the first 7 days). The graphs show the differences between quantities of metal ions released for each observed element. The largest quantity of ions released was measured for Cu at each time point and for every archwire used (eg, cumulative Cu release at pH 3.5 from SS archwire: 19,893 ppb). Titanium ions displayed the lowest release rate, totaling a maximum of 2.5 ppb from NiTi archwire at pH 3.5. In both solutions, the quantity of released ions decreased in the same order, namely, Cu, Fe, Ni, Cr, Zn, and Ti.

The pH value of the solution significantly influenced release of ions from all observed elements (Figures 1 and 2). The average daily release for each observed

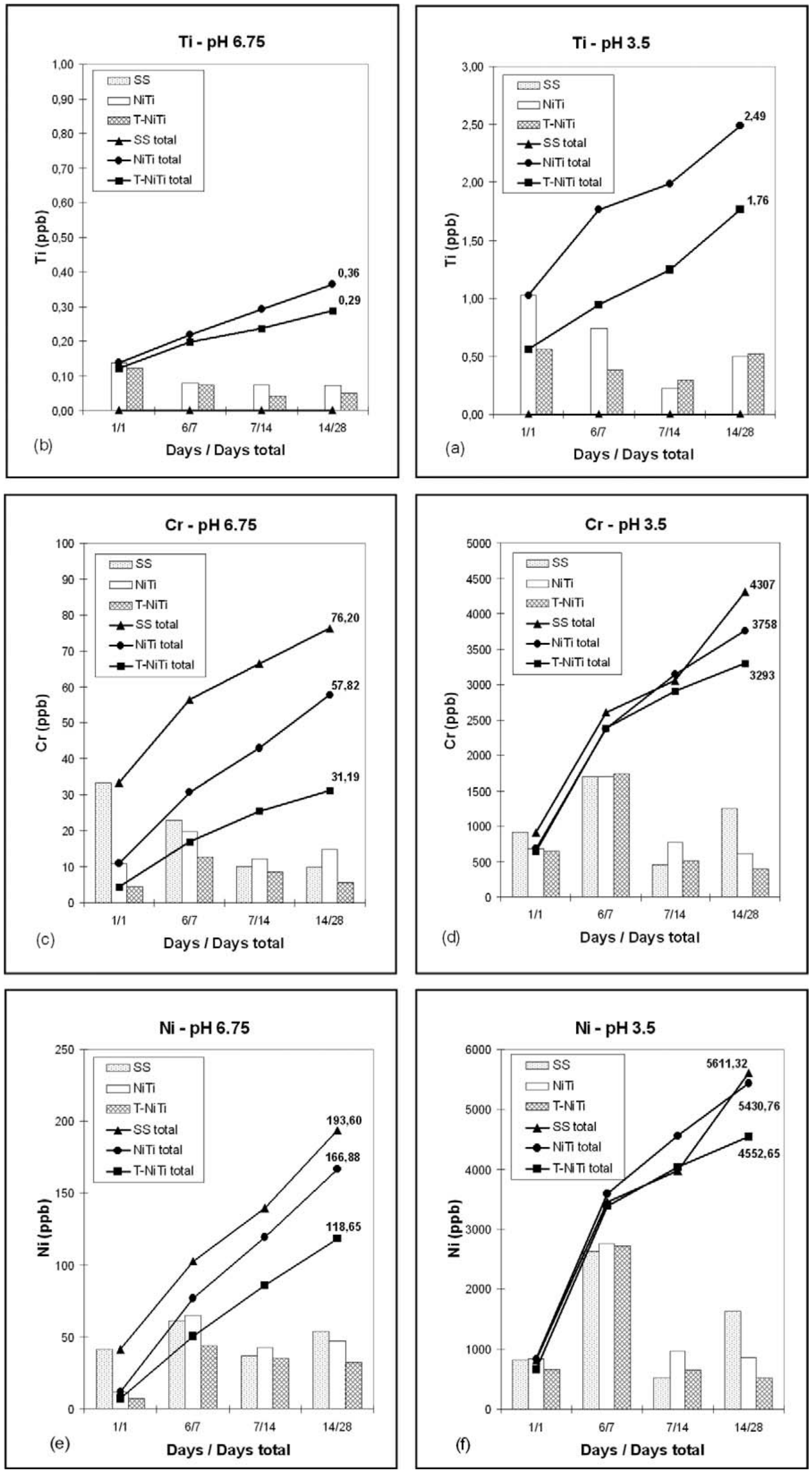

Figure 1. Juxtaposed graphs of the release of ions of titanium (Ti), chromium (Cr), and nickel (Ni) from constructed orthodontic appliances in artificial saliva of different pH values. Values on the bar graphs represent the means from three samples that contain the same wire.

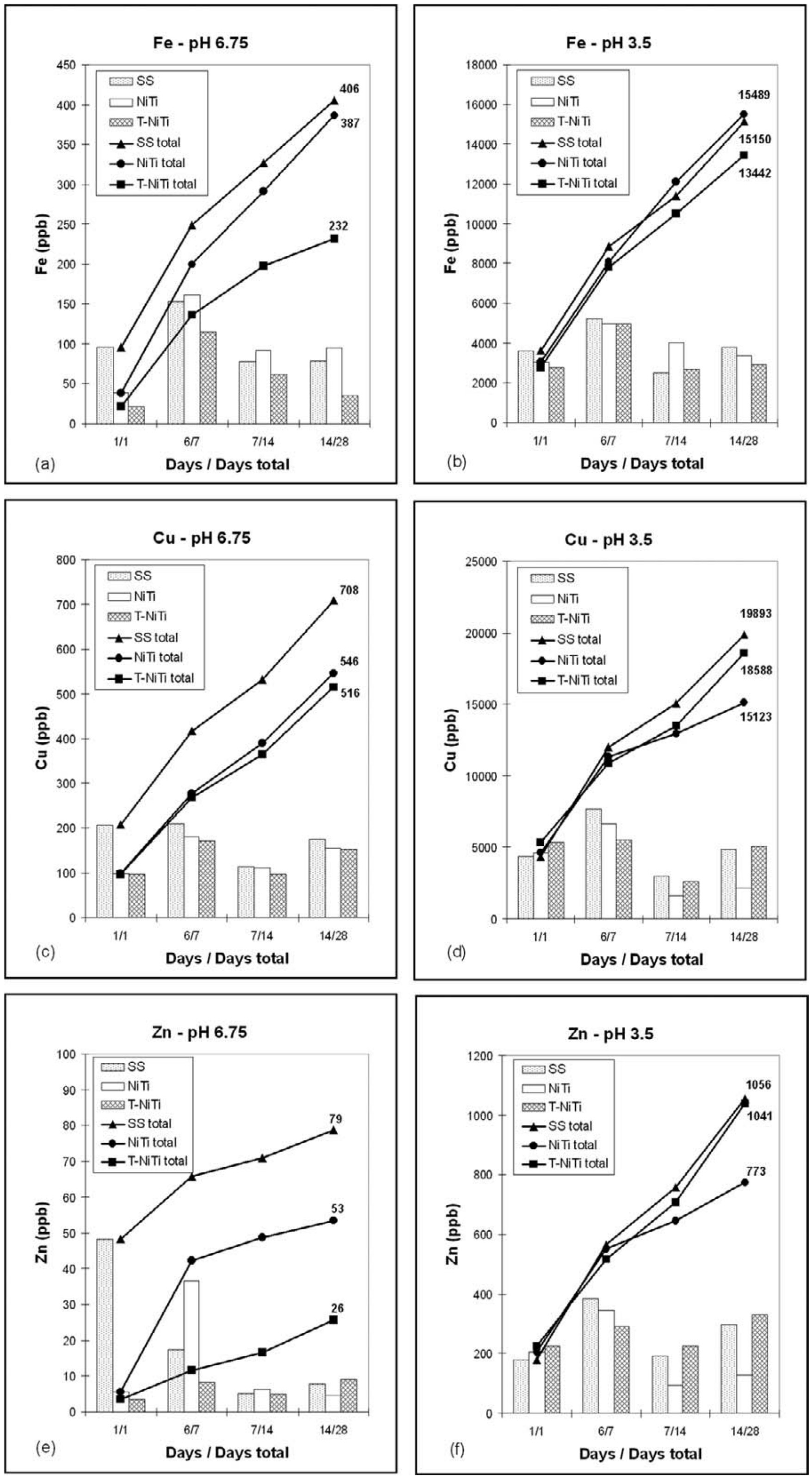

Figure 2. Juxtaposed graphs of the release of ions of iron (Fe), copper (Cu), and zinc (Zn) from constructed orthodontic appliances in artificial saliva of different pH values.

Table 1. Average Daily Release by Time Period for pH = 6.75[a]

Archwire	Time Period, Days	Ti Mean	Ti SD	Cr Mean	Cr SD	Fe Mean	Fe SD	Ni Mean	Ni SD	Cu Mean	Cu SD	Zn Mean	Zn SD
SS	1	0.00	0.00	33.43	24.05	96.06	57.14	41.66	33.99	209.63	105.93	50.32	16.02
	6	0.00	0.00	3.83	1.93	25.55	10.00	10.21	2.68	35.19	2.75	3.38	1.95
	7	0.00	0.00	1.43	0.69	11.08	5.89	5.28	1.87	16.63	1.76	1.16	0.14
	14	0.00	0.00	0.70	0.10	5.62	1.47	3.84	0.86	12.72	2.43	0.69	0.14
NiTi	1	0.14	0.04	10.49	3.90	38.47	15.67	11.77	2.84	99.83	13.07	7.55	2.98
	6	0.01	0.00	3.30	0.95	26.93	5.44	10.83	3.49	30.26	3.44	6.44	2.12
	7	0.01	0.01	1.76	0.34	13.07	4.01	6.13	1.39	16.12	0.90	1.32	0.37
	14	0.01	0.00	1.06	0.21	6.81	1.70	3.38	1.67	11.30	1.16	0.55	0.20
Thermo NiTi	1	0.12	0.02	4.39	1.99	21.18	6.43	7.12	1.33	98.39	3.14	6.38	1.65
	6	0.01	0.00	2.10	0.84	19.11	6.28	7.26	1.10	28.96	3.73	1.85	0.40
	7	0.01	0.00	1.23	0.80	8.79	3.79	5.06	1.57	14.02	0.94	1.13	0.28
	14	0.00	0.00	0.40	0.15	2.50	0.59	2.33	0.77	10.95	1.03	0.72	0.39

Average Daily Release, ppb/Day.

[a] Cr indicates chromium; Cu, copper; Fe, iron; Ni, nickel; NiTi, nickel-titanium; SD, standard deviation; SS, stainless steel; Ti, titanium; and Zn, zinc.

element and for every time point is presented in Tables 1 and 2. These results show that the largest daily ion release was noticed after the first day of exposure to the solution. At each subsequent time point, the daily release continued to decrease, reaching severalfold smaller values at the end point.

Figures 3 and 4 show changes in levels of released ions over time. The release of Cr, Fe, Ni, Cu, and Zn from SS was significantly greater compared with other wires at early time points (days 1 and 7) at neutral pH, but not at pH 3.5. At pH 3.5, the release of ions from all three types of wires showed a very similar pattern, with remarkable decreases noted after days 1 and 7. Overall levels of released ions were consistently severalfold higher at pH 3.5 than at pH 6.75. The release of Ti from NiTi and T-NiTi was similar over the time course at both pH values, with a marked decline by day 7. The SS does not contain Ti.

Table 3 shows the results of repeated measures ANOVA used to test the effects of two variables—the type of archwire and the immersion time—on the release of ions. When the influence of the type of archwire on the quantity of released ions was analyzed, a statistically significant difference ($P < .05$) was noted for ions of Ti and Zn in a solution with pH value of 6.75. In the solution with pH value of 3.5, statistically significant differences were found only for the release of ions of Ti. Statistically significant differences in immersion time were noted in all cases. Analysis of the interaction of observed variables (ie, when ion release kinetics is compared for all three types of appliances over all four time periods) revealed statistically significant differences in the release of ions of Ti, Cr, Fe, Cu, and Zn in the solution with a higher pH value. In the solution with a lower pH value, a statistically significant difference was apparent only for ions of Ti.

Table 2. Average Daily Release by Time Period for pH = 3.5[a]

Archwire	Time Period, Days	Ti Mean	Ti SD	Cr Mean	Cr SD	Fe Mean	Fe SD	Ni Mean	Ni SD	Cu Mean	Cu SD	Zn Mean	Zn SD
SS	1	0.00	0.00	913.7	181.9	3642.9	934.2	815.3	153.3	4355.3	842.7	183.60	63.76
	6	0.00	0.00	282.2	63.3	874.2	135.3	439.9	94.7	1279.8	224.1	65.07	6.42
	7	0.00	0.00	64.0	26.4	360.7	68.1	74.7	36.7	431.9	94.2	28.17	1.90
	14	0.00	0.00	89.4	11.9	270.3	37.5	116.7	4.6	346.7	81.1	21.62	3.14
NiTi	1	1.02	0.61	682.7	61.2	3082.7	948.6	835.1	88.9	4663.5	1086.0	211.16	26.67
	6	0.12	0.11	281.9	71.7	837.4	137.1	459.5	82.2	1110.3	235.9	58.37	13.47
	7	0.03	0.01	110.0	22.1	577.2	63.2	138.9	43.4	230.1	102.3	13.85	7.83
	14	0.04	0.01	43.9	8.7	242.1	22.6	61.9	25.6	157.6	103.0	9.51	3.42
Thermo NiTi	1	0.56	0.13	644.0	282.7	2799.1	890.1	661.2	234.8	5352.1	748.8	229.50	52.73
	6	0.06	0.02	289.4	53.3	836.5	146.8	454.0	83.6	924.2	109.5	49.25	10.36
	7	0.04	0.02	74.5	28.5	388.2	172.3	92.2	44.9	375.2	178.1	27.66	3.81
	14	0.03	0.03	28.0	5.5	211.1	58.9	37.3	5.9	363.1	99.8	24.07	4.65

Average Daily Release, ppb/Day.

[a] Cr indicates chromium; Cu, copper; Fe, iron; Ni, nickel; NiTi, nickel-titanium; SD, standard deviation; SS, stainless steel; Ti, titanium; and Zn, zinc.

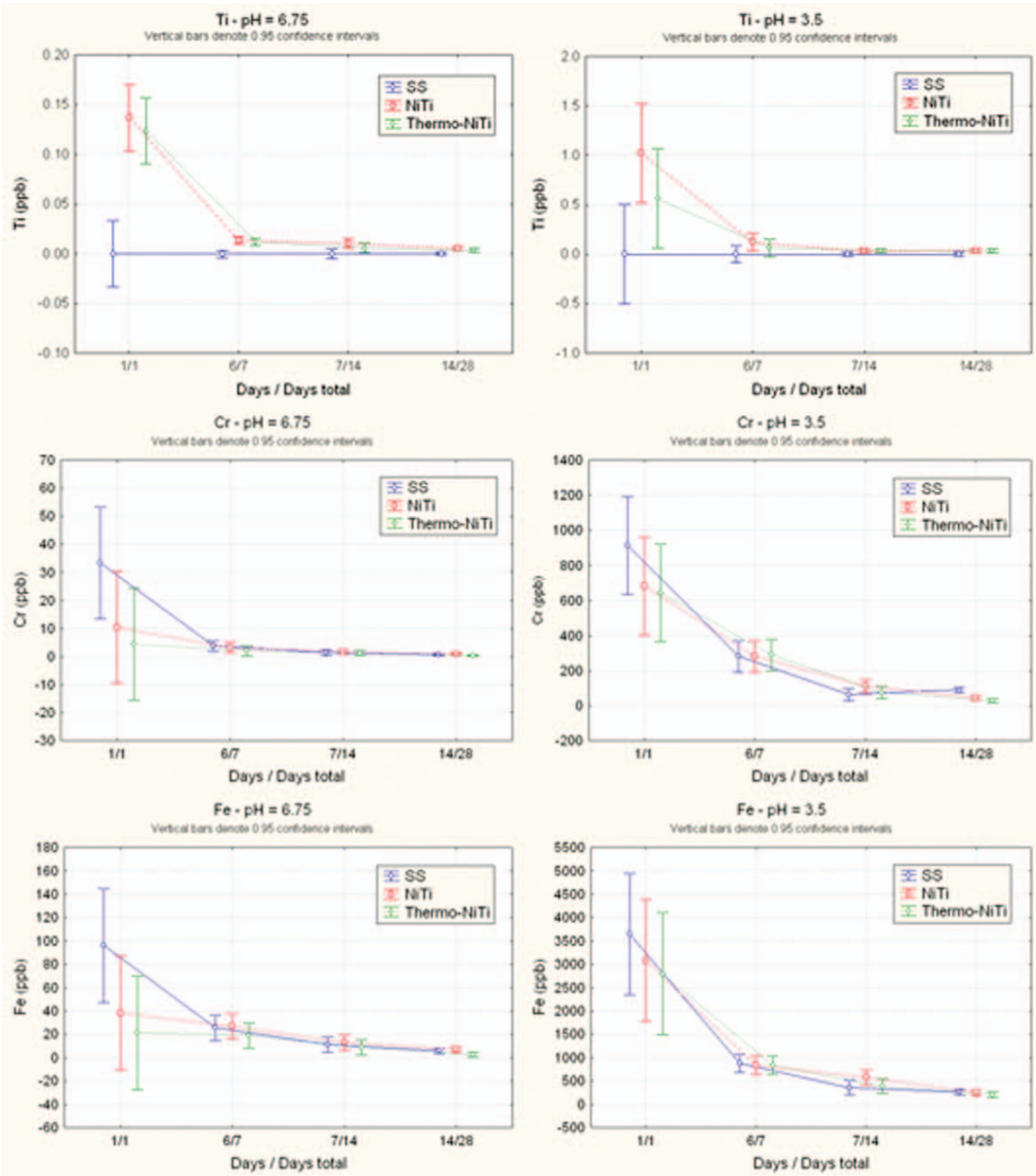

Figure 3. Release of ions of titanium (Ti), chromium (Cr), and iron (Fe) over the time course of the experiment.

DISCUSSION

This study emphasizes the importance of several factors that can influence the release of metal ions from fixed orthodontic appliances, namely, the type of alloy, the pH of the solution, and the length of immersion. The appliance consisted of the brackets and wires, and it is likely that the brackets contributed to the quantities of released ions. However, because the brackets consisted of the same material in all samples, their contribution was constant and did not influence relative comparisons of ions released from wires. This study demonstrates that the release of Ti, Ni, Cr, Fe, Zn, and Cu ions depended not only on the pH value of the solution, but also on the length of exposure and, to a smaller degree, on the material that made up the archwire used. Although the quantities of released metal ions measured in this and similar studies[22] cannot be directly applied to in vivo conditions, they are useful for relative comparisons and for determination of the effect of each individual variable (eg, pH) on ion release without the influence of external factors.

Other studies have suggested that the quantity of released metal ions is not proportional to the content

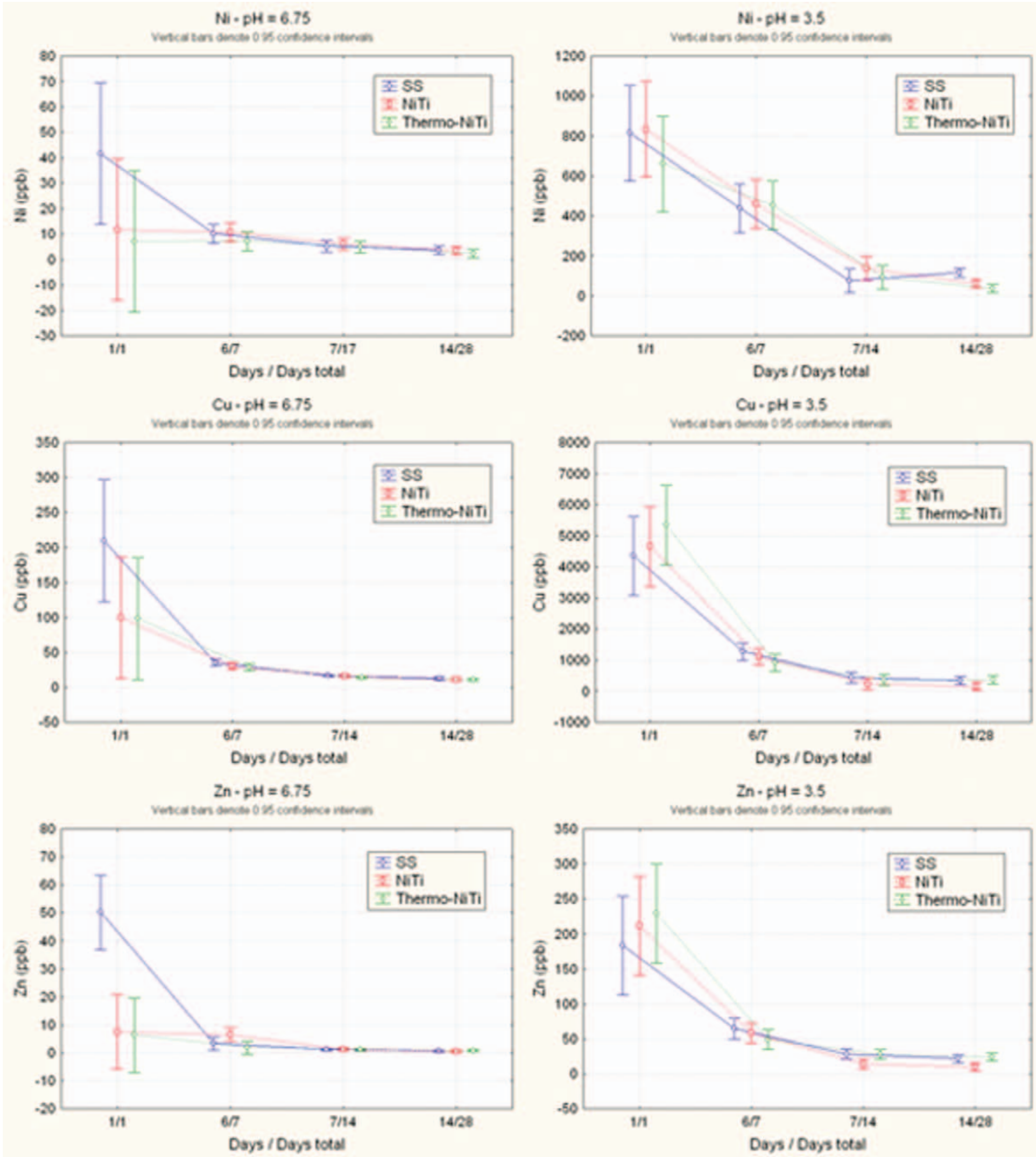

Figure 4. Release of ions of nickel (Ni), copper (Cu), and zinc (Zn) over the time course of the experiment.

Table 3. Results of Repeated Measure ANOVA Statistical Analysis[a]

Element	Ti		Cr		Fe		Ni		Cu		Zn	
pH	6.75	3.50	6.75	3.50	6.75	3.50	6.75	3.50	6.75	3.50	6.75	3.50
Main effects												
Archwire (a)	0.000*	0.008*	0.073	0.301	0.080	0.534	0.112	0.413	0.100	0.576	0.002*	0.640
Immersion time (b)	0.000*	0.000*	0.001*	0.000*	0.000*	0.000*	0.010*	0.000*	0.000*	0.000*	0.000*	0.000*
2-Way interaction (a*b)	0.000*	0.004*	0.023*	0.200	0.016*	0.679	0.061	0.526	0.028*	0.328	0.000*	0.504
Model	0.000*	0.002*	0.018*	0.028*	0.005*	0.000*	0.001*	0.001*	0.001*	0.002*	0.000*	0.001*

* Statistically significant difference at $P < .05$.

[a] ANOVA indicates analysis of variance; Cr, chromium; Cu, copper; Fe, iron; Ni, nickel; Ti, titanium; and Zn, zinc.

of metal in the alloy.[10,22–24] Although NiTi wires have a high percentage of nickel, the quantity of released nickel ions is smaller than that released from SS wire. This can be explained by the selective melting phenomenon and by formation of the titan–oxide layer, which is extremely corrosion resistant.[25]

Our results showed the greatest release of ions during the first 7 days and a gradual decline thereafter. This cannot be ascribed to saturation of the solution with metal ions because the solution was changed for every time period. This kinetics of ion release coincides with results from other studies[1,10,26] and can be explained by an initial surge of ion release from the metal surface or by formation of a stable oxide layer that slows down further ion release.[27] Decreasing the pH from 6.75 to 3.5 increased the release of ions on average 37-fold, with the largest increase for chromium (1:106) and the smallest for titanium (1:7). These results confirm the hypothesis that low pH values reduce the resistance of dental alloys to corrosion.[26,28]

The measured quantities of released metal ions are insignificant from a toxicologic standpoint. The average amount of daily metal ion release (over the 28 days) is well below the daily dietary intake level (eg, Fe, 6-8 mg; Zn, 4-6 mg; Ni, 200-300 μg; Cr, 50-200 μg).[1,21] Thus, a systemic toxic effect from orthodontic appliances is highly unlikely. However, even such small quantities of metal ions can cause allergic reactions, especially because fixed orthodontic appliances remain in the oral cavity for a long time (2 to 3 years). For an allergic reaction to occur in the oral mucous membrane, antigenic potential has to be 5 to 12 times stronger than that on the skin surface. However, various clinical manifestations of hypersensitive reactions to fixed orthodontic appliances have been reported.[10,23] Types of lesions and symptoms associated with contact stomatitis are sometimes difficult to distinguish from mechanical damage to the mucous membrane caused by a fixed orthodontic appliance.[24] Low concentrations of dissolved metal ions can affect cells of the mucous membrane, which are in direct contact with the alloy. Moreover, it was reported that nickel ions released from dental alloys can accumulate in the cells over time, and this may have multiple harmful effects on cells,[29] including suppression of the chemotaxis of leukocytes and changes in DNA synthesis and in enzyme activity.[27,30]

Silver solder, which is a constituent part of brackets, contains copper and zinc, which were released in significant quantities in this study. Both metals are considered highly cytotoxic and are associated with subacute clinical symptoms like glossitis, metal taste, gingival bleeding, and gingivitis,[31] as well as a decrease in corrosion resistance.[21,24,28]

The release of metal ions from dental alloys is a phenomenon that cannot be avoided; it is difficult to find a material that will be fully stable within an organism and will show no signs of biodegradation. A growing number of recent studies are investigating the problem of biocompatibility with the goals of (1) determining the upper limit of biological tolerance and (2) finding means through which the release of ions will be kept within these limits. The present study identified the effects of changes in pH and of the archwire material on the release of metal ions. However, the absorption of released metal ions and their effects on oral tissues remain to be examined in future in vivo studies.

CONCLUSIONS

- All three observed parameters—chemical composition of the archwire, pH value of the artificial saliva, and time of exposure to the solution—influenced ion release.
- Statistically significant stimulation of ion release at lower pH ($P < .05$), which is in line with the hypothesis that organic acids in dentobacterial plaque affect the release of ions, emphasizes the major role of oral hygiene in minimizing corrosion.
- The most significant release of all analyzed metal ions was measured after the first or the second observed time period, which supports the role of oxide layers in slowing down a corrosive process on the metal surface.
- Release of metal ions was influenced by composition of the orthodontic archwire, but this was not proportional to the content of metal in the wire.
- Quantities of all released ions were below toxic levels and did not exceed the daily dietary intake. However, these levels are sufficient to cause an allergic reaction because of the high haptenic potential of released elements.

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