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Release of nickel and chromium from metallic brackets used in orthodontic treatment: an in vitro study

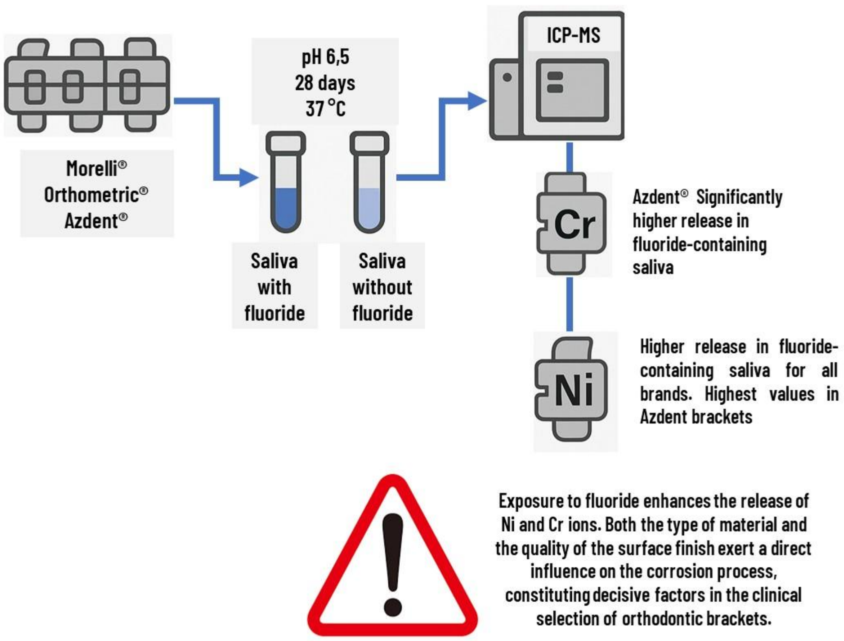
Edelmira Diana Durand-Zea[1] **Tania Carola Padilla-Cáceres**[1] **Juan Carlos Tuesta Hidalgo**[2] **Nadia Rodríguez Hamamura**[3] **Roy Alexander Arévalo Pérez**[2] **Gaelord Vladimir Huacasi-Supo**[1]

[1]Universidad Nacional del Altiplano Puno – UNAP. Puno, Peru.
[2]Universidad Nacional Autónoma de Alto Amazonas – UNAAA. Yurimaguas, Peru.
[3]Universidad Nacional de Ingeniería – UNI. Lima, Peru.
E-mail: tpadilla@unap.edu.pe

Graphical Abstract

Highlights

- *There is a high demand for metallic brackets due to the high prevalence of dental malocclusions.*
- *Stainless steel brackets are composed of Ni, Cr, and other elements that may be released into the oral cavity.*
- *The release of Ni and Cr ions is greater in the presence of fluoride.*
- *Nickel may induce type IV hypersensitivity, characterized mainly by gingival hypertrophy, angular cheilitis, and desquamation.*



Abstract

The objective of this study was to evaluate the release of nickel (Ni) and chromium (Cr) ions from conventional metallic brackets of different commercial brands immersed in artificial saliva with and without fluoride. A total of 600 metallic brackets (Morelli®, Orthometric®, and Azdent®) were randomly allocated into an experimental group (fluoride-containing artificial saliva) and a control group (fluoride-free artificial saliva), both maintained at pH 6.5 and 37 °C for 28 days. Ni and Cr ion release was determined using inductively coupled plasma mass spectrometry (ICP-MS). Data were analyzed using the Mann–Whitney U and Kruskal–Wallis tests. The results showed that Ni ion release was higher in the presence of fluoride for all brands evaluated, with a tendency toward higher values in Azdent® brackets (383.36 µg/L). Regarding Cr ions, Azdent® brackets exhibited significantly greater release in fluoride-containing saliva (1.52 µg/L), whereas no significant differences were observed for Morelli® and Orthometric® groups. When comparing the three brands in fluoride-containing artificial saliva, all exhibited increased ion release, which was significant for Azdent® ($p < 0.05$). Exposure to fluoride increases Ni and Cr release, particularly in Azdent® brackets. The material and surface finish influence corrosion, constituting a key factor in clinical orthodontic selection.

Keywords: Metallic Brackets. Nickel Ion. Chromium Ion. Fluoride. Salivary pH.

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INTRODUCTION

The high demand for metallic brackets is a consequence of the elevated prevalence of malocclusions in Latin America, estimated at 53%[1,2]. According to the World Health Organization (WHO), these conditions represent the third highest prevalence (70%) among oral diseases in Peru[3].

Stainless steel brackets are primarily composed of a Ni–Cr alloy, in addition to other elements such as iron, molybdenum, and carbon, which confer properties including luster, malleability, corrosion resistance, and hardness[4,5,6]. However, continuous exposure to the oral environment characterized by fluctuations in pH, temperature, oxygen levels, and the presence of fluoride can alter the passive surface layer of stainless steel and promote the release of metal ions[4,5].

Reports indicate that Ni may trigger type IV hypersensitivity, manifested as delayed allergic reactions mediated by T lymphocytes in patients wearing metallic orthodontic appliances[7]. This condition is primarily characterized by gingival hypertrophy, angular cheilitis, lip desquamation, facial erythema, irritation, pruritus, eczema, and pain. Elevated Ni concentrations may also cause respiratory problems such as asthma, as well as nausea, diarrhea, vomiting, or abdominal cramps, and may affect the liver and kidneys; thus, its ionic release has both local and toxicological implications[8,9].

The release of Ni and Cr ions from metallic brackets becomes even greater in the presence of fluoride[10]. It has been demonstrated that non-toxic concentrations may still be sufficient to induce biological alterations in the oral mucosa[11].

The prevalence of nickel hypersensitivity among patients wearing orthodontic appliances reaches 30%, occurring more frequently in young women[7,12].

The effectiveness of orthodontic treatment may also be compromised by changes in the material's resistance to wear and fatigue[13,14]. Corrosion—resulting from chemical or electrochemical reactions between the material and the environment—induces modifications in its properties and characteristics[15].

Moreover, the mechanical properties of brackets and orthodontic archwires may be affected by topical exposure to fluoride-containing agents, which promote increased ion release, especially under acidulated fluoride conditions[10]. Such changes not only reduce the durability of the device but also increase friction at the bracket–archwire interface, impairing the biomechanical efficiency of orthodontic treatment[15,16,17].

Additionally, low-pH fluoridated mouthrinses and toothpastes available on the market may reduce the corrosion resistance of stainless steel and titanium alloys, increasing Ni and Cr release, particularly when combined with the mechanical friction generated by orthodontic appliances[9,18,19,20]. Studies show that brackets exposed to fluoridated mouthrinses exhibit greater ion release, especially Ni and Cr, and caution is therefore advised in their use[21]. Consequently, evaluating the biocompatibility and corrosive behavior of different commercial brands of brackets is essential, particularly under conditions that simulate the oral cavity[4].

Despite the available literature on corrosion in orthodontic materials, comparative studies among different brands of metallic brackets tested under controlled experimental conditions that reproduce the oral environment remain limited. Therefore, the aim of this study was to evaluate the release of Ni and Cr ions from conventional metallic brackets of three commercial brands in artificial saliva with and without fluoride, contributing to a broader understanding of ionic behavior and its impact on clinical practice.

METHODOLOGY

A descriptive experimental in vitro study was conducted to evaluate the release of Ni and Cr ions from conventional metallic brackets exposed to controlled conditions in Fusayama–Meyer artificial saliva, with and without fluoride.

A total of 600 Roth-prescription metallic brackets, 0.022-slot, from three commercial brands were used: Morelli® (Brazil), Orthometric® (Brazil), and Azdent® (China). Each batch consisted of 200 brackets, evenly distributed into two groups:

- Group 1 (control): fluoride-free artificial saliva.
- Group 2 (experimental): artificial saliva containing 1000 ppm fluoride.

Twenty brackets corresponding to a complete orthodontic kit (from the right second premolar to the left second premolar, in both arches) were placed into sterile 15 ml polypropylene centrifuge tubes (Samplix®).

Each tube contained 10 ml of Fusayama–Meyer artificial saliva at pH 6.5, with or without fluoride

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(1000 ppm), according to the assigned group.

A total of 15 tubes were prepared for the experimental group (fluoride-containing saliva) and 15 tubes for the control group (fluoride-free saliva). Samples were maintained at 37 °C for 28 days in an incubator chamber under controlled temperature and without light exposure. Each group included 15 replicates per brand.

At the end of the immersion period, Ni and Cr ion release was determined using inductively coupled plasma mass spectrometry (ICP-MS). Prior to analysis, each tube was homogenized and its contents weighed on a microanalytical balance to ensure consistency in measurements.

The concentration of 1000 ppm fluoride was selected because most commercially available dentifrices and daily-use oral hygiene products contain this fluoride level, reproducing clinical conditions of continuous fluoride exposure similar to those occurring during daily oral hygiene in orthodontic patients[22].

Procedure for assessing nickel and chromium ion release

Prior to evaluation, brackets were verified to show no visible signs of alteration or deterioration. All brackets were inspected in the same manner by the same observer, with normal chromatic vision, using a reflector with a minimum light intensity of 1000 lx and at a distance of less than 25 cm.

Bracket surfaces were cleaned in an ultrasonic bath for 2 minutes in ethanol, rinsed with water, and dried with oil-free, moisture-free compressed air.

To control contamination, negative controls (solution without brackets) and automatic pipettes with filtered tips were used. All procedures were performed under an exhaust hood to minimize environmental contamination.

Static immersion test of orthodontic brackets

This procedure was performed using the prepared Fusayama–Meyer artificial saliva solutions: fluoride-free for the control group and 1000 ppm fluoride for the experimental group. Sterile disposable 15 ml polypropylene tubes with caps were used, each containing 10 ml of artificial saliva with or without fluoride, followed by insertion of the corresponding brackets.

All samples were maintained at 37 °C, pH 6.5, for 28 days under minimal mobility. At the end of the experimental period, ion release of Ni and Cr was observed and quantified for each sample.

Inductively coupled plasma mass spectrometry (ICP-MS) analysis, thermo fisher scientific, model ICAP-RP

This technique offers high sensitivity and precision for quantifying trace metals in aqueous solutions. In the present in vitro study, brackets were immersed in a medium simulating the oral environment, such as artificial saliva, under controlled temperature and pH. Aliquots of the medium were collected to analyze the concentrations of released Ni and Cr.

ICP-MS allows detection of extremely low concentrations, even in the parts-per-billion (ppb) range, due to its ability to ionize elements in high-temperature argon plasma and separate them according to mass-to-charge ratio (m/z). Instrument calibration was performed using standards of known Ni and Cr concentrations, and an internal standard, such as indium (In), was used to correct potential instrumental variations[23].

Data were recorded in an electronic matrix and analyzed using IBM SPSS Statistics v.27. Normality was assessed using the Shapiro–Wilk and Kolmogorov–Smirnov tests. As the distributions were non-normal, nonparametric tests were applied: Mann–Whitney U (intragroup comparisons) and Kruskal–Wallis (intergroup comparisons). p-values were reported to estimate the practical magnitude of observed differences. The significance level was set at $p < 0,05$.

RESULTS

Analysis of Ni ion release using inductively coupled plasma mass spectrometry (ICP-MS) showed that, for the Azdent® brand, the mean Ni release was 10.62 µg/L in fluoride-free saliva and 383.36 µg/L in fluoride-containing saliva; this difference was statistically significant ($p = 0.009$). For the Morelli® brand, the mean Ni release was 0.14 µg/L (without fluoride) versus 1.26 µg/L (with fluoride), with no significant differences ($p = 0.841$). For Orthometric®, the means were 0.34 µg/L (without fluoride) and 2.20 µg/L (with fluoride), also without significant differences ($p = 0.310$). (Table 1), (Figure 1).

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Comparison among brands using the Kruskal–Wallis test revealed overall differences for fluoride-free saliva (p = 0.006) and for fluoride-containing saliva (p = 0.005), with Azdent® exhibiting the highest values in both conditions. (Table 1), (Figure 1).

Table 1 - Nickel (Ni) release by brand (Morelli®, Orthometric®, Azdent®) in artificial saliva with and without fluoride (pH 6.5; 37 °C; 28 days). Comparison of Ni ion release from metallic brackets immersed in artificial saliva with and wi-thout fluoride. Puno, Peru; april–may 2024.

BRACKETS	WITHOUT FLUORIDE µg/L	WITHOUT FLUORIDE µg/L	p-value
MORELLI®	0.14 [0.00 -0.50]	1.26 [0.00 – 5.90]	0.814
ORTHOMETRIC®	0.34 [0.00 – 0.50]	2.20 [0.00 – 7.40]	0.246
AZDENT®	10.62 [6.40 – 13.30]	383.36 [177.30 – 625.80]	0.009
	p=0.006	**p=0.005**	

Source: Authors' elaboration based on ICP-MS measurements performed at the Biotechnology Laboratory, Universidad Nacional Autónoma de Alto Amazonas, Yurimaguas, Peru.
Note: Nonparametric tests: between-group = Kruskal–Wallis; within-group = Mann–Whitney U; α = 0.05. Values are expressed in µg/L.

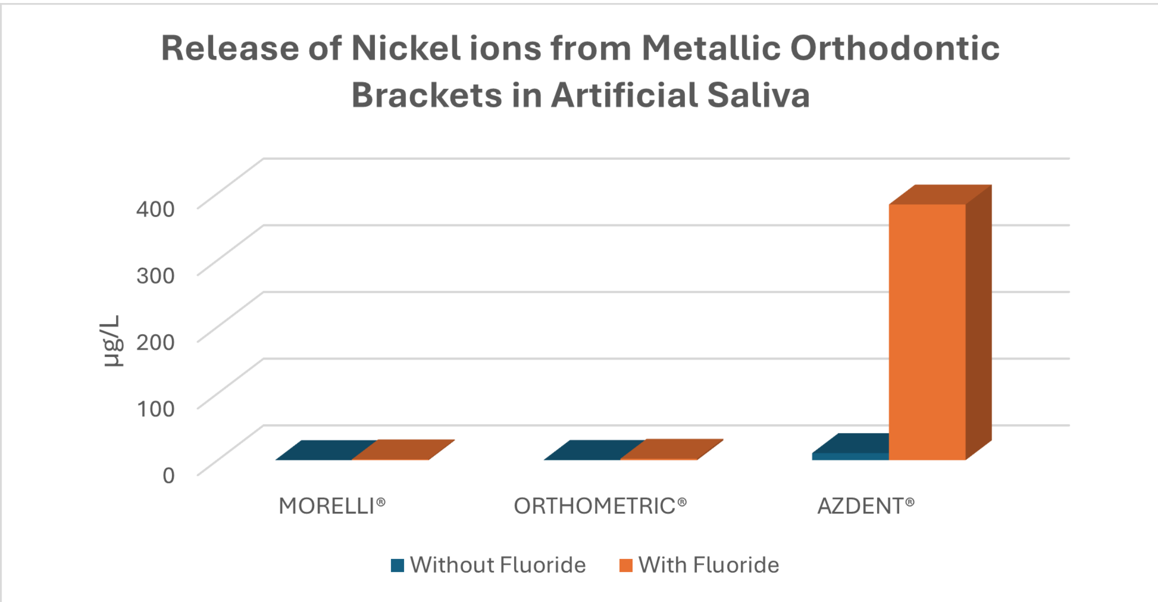

Figure 1 - Bar graphs are shown. In the presence of fluoride, all three groups tended to exhibit higher Ni values; however, a significant intragroup increase was observed only for Azdent® (p = 0.0095), while Morelli® (p = 0.814) and Orthometric® (p = 0.246) showed no significant differences. In the intergroup analysis under fluoride exposure, Azdent® presented the highest concentrations (Kruskal–Wallis p = 0.005), highlighting its comparatively greater ion release.

In Table 2 and Figure 2, the results of Cr ion release in artificial saliva with and without fluoride are presented. For Morelli® brackets, the mean Cr concentration in fluoride-free artificial saliva was 0.22 µg/L, whereas the fluoride-containing group showed a mean of 0.14 µg/L, with statistically significant differences (p = 0.042). For Orthometric®, both groups exhibited a mean of 0.22 µg/L (p = 0.905).

For Azdent® brackets, fluoride-free artificial saliva showed a mean of 0.30 µg/L, while the fluoride-containing group showed a mean of 1.52 µg/L, with statistically significant differences (p = 0.005).

Interbrand comparison in fluoride-free saliva using the Kruskal–Wallis test demonstrated significant overall differences under both conditions.

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Table 2 - Comparison of Cr ion release from metallic brackets immersed in artificial saliva with and without fluoride. Puno, Peru; april–may 2024.

BRACKETS	WITHOUT FLUORIDE µg/L	WITHOUT FLUORIDE µg/L	p-value
MORELLI®	0.22 [0.20-0.30]	0.14 [0.10-0.20]	0.042
ORTHOMETRIC®	0.22 [0.20-0.30]	0.22 [0.10-0.30]	0.905
AZDENT®	0.30 [0.30-0.30]	1.52 [0.60-2.70]	0.005
	p=0.006	**p=0.005**	

Source: Authors' elaboration based on ICP-MS measurements conducted at the Biotechnology Laboratory, Universidad Nacional Autónoma de Alto Amazonas, Yurimaguas, Peru.
Note: Nonparametric tests: between-group – Kruskal–Wallis; within-group – Mann–Whitney; α = 0.05. Values expressed in µg/L.

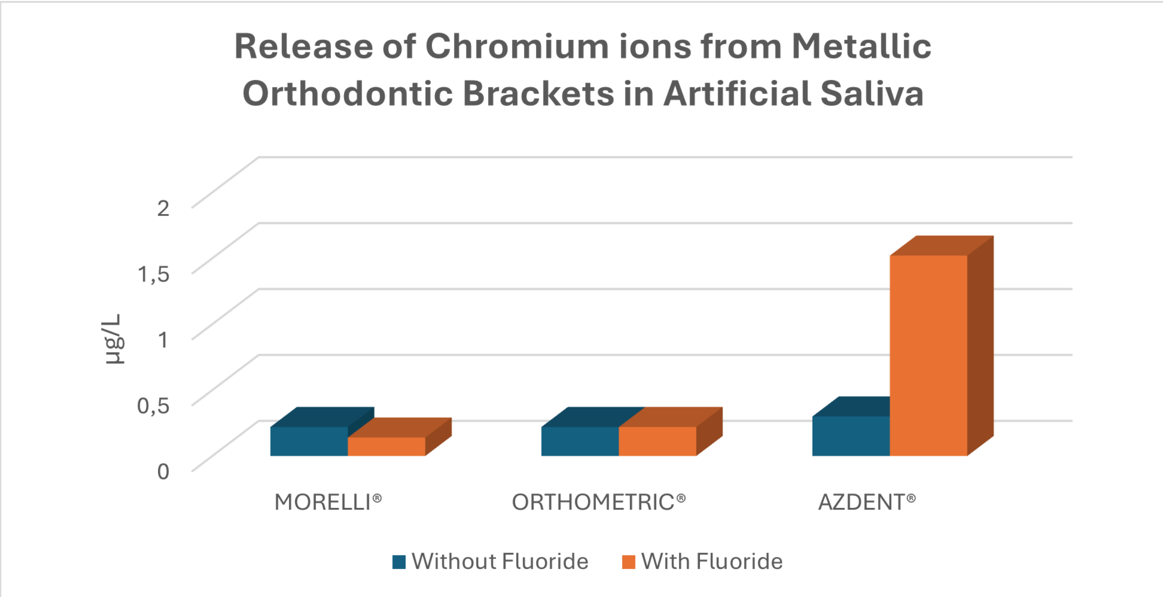

Figure 2 - Chromium (Cr) release by brand (Morelli®, Orthometric®, Azdent®) in artificial saliva with and without fluoride (pH 6.5; 37 °C; 28 days). Bar charts are shown. In the presence of fluoride, the Azdent® group exhibits the highest Cr release (p = 0.005); however, no differences were observed between conditions for Orthometric® (p = 0.905), and for Morelli® the difference was statistically significant (p = 0.042). In the intergroup analysis with fluoride, Azdent® presented the highest concentrations (Kruskal–Wallis p = 0.005), underscoring its relatively greater ion release.

DISCUSSION

The most important factor in determining the biological safety of a metallic alloy is corrosion, which can affect aesthetics, strength, and biocompatibility[24]. Corrosion is an electrochemical reaction between metallic materials and the surrounding environment. In the oral cavity, this wet corrosion occurs through the release of positive metal ions from orthodontic alloys. The main corrosion products of stainless steel brackets are iron, chromium (Cr), and nickel (Ni)[22]. The release of Ni and Cr ions may occur due to the presence of fluoride ions in dentifrices and mouthrinses; fluoride can degrade stainless steel surfaces by damaging the oxide layer and promoting the release of ions such as Ni and Cr[25].

The corrosion resistance of metals depends on the galvanic series of metals and alloys. The more electronegative a material is, the greater its susceptibility to corrosion[19,26].

Systemic and local toxicity, as well as the carcinogenic potential of an alloy, result from the elements released in the mouth during the corrosion

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process; therefore, alloys with high corrosion resistance should be preferred for clinical practice[27].

Matusiewicz[28] emphasizes that several dental materials composed of metallic alloys such as stainless steel brackets are capable of releasing a variety of ions in the presence of saliva, with Ni, Cr, iron, magnesium, and copper being the most relevant. In the present study, the Azdent® brand showed the highest values of Ni and Cr ion release. This finding may be attributed to differences in the metallographic composition of the alloy, lower purity control of the stainless steel, or a less homogeneous surface finish factors that increase susceptibility to corrosion. Previous studies support this interpretation, demonstrating higher ion release in lower-cost brands or those with less controlled manufacturing processes[21,25]. Similarly, Wu *et al.*[29] reported that surface roughness directly influences metallic ion release due to the increased exposed area in corrosive environments.

Regarding Ni ion release, brackets from Morelli®, Orthometric®, and Azdent® exhibited greater release in fluoride-containing saliva, with significant differences for Azdent® ($p < 0.005$). For Cr ions, Azdent® brackets showed significant differences between the control and experimental groups; in contrast, no statistically significant differences were observed for Orthometric®. These findings are consistent with those of Yanisarapan[25], who in 2018 reported that stainless steel brackets and wires exposed to artificial saliva released up to 265.6 mg/L (± 27.9 mg/L) of Ni, while Cr levels reached 112.0 mg/L (± 10.9 mg/L). Likewise, Tahmasbi evaluated galvanic corrosion products in brackets and wires from four brands (Dentaurum, American Orthodontic, ORJ, and Shinye), exposing them to a 0.05% sodium fluoride mouthrinse for 28 days, and found that Ni ion release was significantly higher in the Shinye and ORJ brands compared to the others[21].

The results of this study also agree with those of Hajjar[30], who assessed metal ion release from standard and low-cost brackets at pH 4.9 and 7.8 in Fusayama–Meyer artificial saliva. Samples were analyzed at 1, 14, and 28 days via inductively coupled plasma mass spectrometry, revealing higher ion release at pH 7.8: on day 28, Cr levels reached 2496.0 µg/L in standard brackets and 3293.3 µg/L in low-cost brackets; for Ni, the values were 1746.7 µg/L and 3240.0 µg/L, respectively. In a review study, Kriswandini and Bagus[22] observed that immersion in artificial saliva for 30 days at pH 6.8 and 37 °C resulted in lower Cr release relative to Ni—possibly because the alloy composition contains less Cr than Ni.

Excessive release of metals such as Cr and Ni may cause changes in the dimensions and shape of the bracket, resulting in structural fragility and affecting human health, since both belong to the group of heavy metals capable of triggering type IV hypersensitivity reactions[31].

Amini, in a case–control study, observed Ni ion concentrations of 18.5 ± 13.5 ng/mL in individuals with fixed orthodontic appliances, with significant differences compared with controls. For Cr, values of 2.6 ± 1.6 ng/mL were recorded in the experimental group and 2.2 ± 1.6 ng/mL in the control group ($p < 0.005$)[32]. Jurela evaluated ion release in metallic and non-metallic brackets before and after orthodontic treatment, finding that Ni release did not differ significantly in metallic brackets; however, Cr release showed significant differences ($p = 0.004$)[33].

Schiff[34] investigated the influence of fluoride-containing mouthrinses on the risk of galvanic coupling corrosion between archwires and brackets, using two types of rinses one containing stannous fluoride and the other sodium fluoride. He observed that, in the bracket/wire coupling, Ni ion release was highest in brackets containing CoCr alloys (109 µg/L), followed by FeCrNi brackets (52 µg/L to 4.2 µg/L). Nahidh[35] concluded that mouthrinse corrosivity depends on the chemical structure of the compound and that the manufacturing process of brackets is among the main determinants of ion release. The variable release profiles observed likely reflect different degrees of surface passivation among brackets, as a hermetic passivation layer would prevent additional corrosion.

Both Cr and Ni may exert toxic effects on human health, depending on their chemical form and route of exposure. Inhalation of hexavalent chromium Cr(VI) is associated with lung, nasal, and paranasal sinus cancers, and its ingestion in drinking water raises concerns regarding gastric cancer risk[2]. Cr(VI) exposure may also cause respiratory irritation, nasal ulceration, asthma, ocular damage, and skin disorders such as allergic dermatitis and ulcers; at the cellular level, it is hematotoxic and genotoxic, affecting blood cells and DNA[20]. In contrast, trivalent chromium Cr(III) is considered an essential trace element with low toxicity, although high doses may cause gastrointestinal disturbances and, rarely, renal and hepatic damage[19].

Ni also poses health risks. Contact dermatitis is a common reaction arising from exposure to objects containing this metal. Inhalation, particularly in occupational settings, is associated with respiratory irritation, occupational asthma, pulmonary fibrosis,

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and increased risk of lung and nasal cancers[32].

Combined exposure to Cr and Ni, common in certain industrial environments, may produce synergistic effects, increasing genotoxic and carcinogenic risk. Thus, minimizing human exposure to both metals is essential[36].

According to the International Agency for Research on Cancer (IARC)[37], certain nickel compounds and hexavalent forms of chromium present evidence of carcinogenicity in humans. In the regulatory context of dentistry, ISO 10271 defines testing methods for evaluating corrosion of metallic materials, whereas ISO 22674 requires that, in static immersion testing, total ion release not exceed 200 μg/cm² in 7 days[38] a criterion used to ensure corrosion resistance. When expressed in comparable units per area, our results remain well below this limit.

Therefore, although exposure to fluoride increased metal ion release, the values obtained do not constitute a significant biological risk, provided that fluoridated products are used at clinically standard concentrations (≈1000 ppm). Nonetheless, caution is recommended for patients with known metal allergies, and alternative brackets such as titanium or ceramic should be considered.

Table 3 - Comparative studies on metal ion (Ni and Cr) release from stainless steel orthodontic brackets.

Estudo (author, year)	Design / model	Materials / brands	Medium / conditions	Ions evaluated	Result (units)	Main finding
Yanisarapan *et al.*, 2018[25] (Orthodontic Waves)	*In vitro*	Stainless steel brackets and archwires	Artificial saliva; fluoride-containing products	Ni, Cr	Ni up to 265.6 mg/L (±27.9); Cr up to 112.0 mg/L (±10.9)	Fluoride increases the release of Ni and Cr; high levels under fluoridated conditions
Tahmasbi *et al.*, 2015[21] (J Dent Res Dent Clin Dent Prospects)	*In vitro*; 28 days	Brackets and archwires (Dentaurum, American Orthodontics, ORJ, Shinye)	Mouthrinse with 0.05% NaF for 28 days	Ni (main)	Ni significantly higher in Shinye and ORJ brands (vs. others)	Differences between brands; NaF enhances galvanic corrosion and Ni release
Hajjar *et al.*, 2021[30] (IMJM)	*In vitro*; 1, 14 y 28 days; ICP-MS	Brackets and archwires (Dentaurum, American Orthodontics, ORJ, Shinye)	Mouthrinse with 0.05% NaF for 28 days	Ni (main)	Ni significantly higher in Shinye and ORJ brands (vs. others)	Differences between brands; NaF enhances galvanic corrosion and Ni release
Kriswandini & Bagus, 2024[22] (Indonesian J Dent Med)	Prolonged exposure (30 days)	Stainless steel brackets	Artificial saliva; pH 6.8; 37 °C; exposure to common dentifrice	Ni, Cr	Cr < Ni (exact values not reported in provided text)	Cr release was lower than Ni; possibly related to alloy composition
Schiff *et al.*, 2006[34] (Eur J Orthod)	*In vitro*; galvanic coupling	Brackets and archwires (CoCr and FeCrNi alloys)	Mouthrinses with stannous fluoride and NaF	Ni (main)	Ni up to 109 μg/L (CoCr); 52–4.2 μg/L (FeCrNi)	Alloy type and mouthrinse influence ion release; higher with CoCr alloys
Amini *et al.*, 2012[32] (Eur J Orthod)	*In vivo*; case–control	Fixed appliances	Patients *vs.* controls	Ni, Cr (in biological fluids)	Ni: 18.5 ± 13.5 ng/mL (patients); Cr: 2.6 ± 1.6 ng/mL (patients) vs. 2.2 ± 1.6 ng/mL (controls); p < 0.005	Higher Ni in users of fixed appliances; significant difference
Jurela *et al.*, 2018[33] (Acta Stomatol Croat)	*In vivo*; pre *vs.* post-treatment	Metallic and ceramic brackets	Patients before and after treatment	Ni, Cr	Ni: no significant differences; Cr: significant difference (p = 0.004)	Cr increases after treatment in some conditions; Ni does not vary significantly

to be continued...

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...*continuation - Table 3.*

Estudo (author, year)	Design / model	Materials / brands	Medium / conditions	Ions evaluated	Result (units)	Main finding
Nahidh *et al.*, 2018[35] (J Contemp Dent Pract)	*In vitro*	*Três tipos de brackets*	Different mouthrinses	Ni, Cr	Variable release depending on mouthrinse (no exact values provided)	Corrosivity depends on chemical structure of the mouthrinse and manufacturing process; surface passivation is decisive
Matusiewicz, 2023[28] (World J Adv Res Rev)	Review (*in vitro* e *in vivo*)	Metallic appliances and alloys	Presence of saliva	Ni, Cr, Fe, Mg, Cu (among others)	—	Devices release multiple ions in saliva; Ni and Cr among the most relevant
Wu *et al.*, 2024[29] (Technology and Health Care)	Experimental (focus on friction)	Esthetic bracket (PEEK) vs. stainless steel (reference)	—	— (indirect relation from text)	—	Greater surface roughness is associated with higher ion release due to increased exposed area

CONCLUSIONS

When comparing the three metallic bracket brands (Morelli®, Orthometric®, and Azdent®), a higher release of Ni ions was observed in fluoride-containing artificial saliva for all of them; however, this difference was statistically significant only for Azdent® brackets.

For Cr, Azdent® brackets also showed significantly higher release, whereas Orthometric® exhibited a non-significant increase. Contrary to expectations, Morelli® brackets showed lower Cr release in the presence of fluoride, which may be associated with differences in alloy composition, passivation processes, or surface finishing during manufacturing.

Overall, all values obtained remained below biologically safe limits, suggesting that the routine use of fluoride-containing products at concentrations around 1000 ppm does not pose a clinically relevant risk regarding metal release. However, continuous monitoring and careful selection of orthodontic materials are essential, prioritizing those with greater corrosion resistance and lower allergenic potential, especially in patients with a history of metal hypersensitivity.

This study presents limitations inherent to the in vitro design, as complete kits of 20 brackets with different morphologies and metal masses were used. Additionally, biological factors such as microbiota, salivary flow, or masticatory forces—which may alter the observed ion-release patterns—were not included.

Future investigations should evaluate the influence of pH variations, the presence of salivary enzymes, and comparisons with ceramic, titanium, or other biocompatible alloy brackets under controlled conditions that more accurately replicate the real clinical environment.

CRediT author statement

Conceptualization: Duran-Zea, E; Padilla-Cáceres, T. Methodology: Duran-Zea, E; Padilla-Cáceres, T; Huacasi-Supo, G. Validation: Padilla-Cáceres, T; Huacasi-Supo, G. Statistical analysis: Duran-Zea, E; Huacasi-Supo, G. Formal analysis: Duran-Zea, E; Padilla-Cáceres, T; Huacasi-Supo, G; Tuesta, J; Rodríguez, N; Arévalo, R. Investigation: Duran-Zea, E; Tuesta, J; Rodríguez, N; Arévalo, R. Resources: Duran-Zea, E. Writing – original draft preparation: Duran-Zea, E; Padilla-Cáceres, T. Writing – review and editing: Duran-Zea, E; Padilla-Cáceres, T; Huacasi-Supo, G; Tuesta, J; Rodríguez, N; Arévalo, R. Visualization: Duran-Zea, E; Padilla-Cáceres, T; Huacasi-Supo, G. Supervision: Duran-Zea, E; Padilla-Cáceres, T; Huacasi-Supo, G; Tuesta, J; Rodríguez, N; Arévalo, R. Project administration: Duran-Zea, E; Tuesta, J; Rodríguez, N; Arévalo, R.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the workreported in this paper.

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