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Biodegradation of Orthodontic Appliances: An Atomic Absorption Spectrophotometric Assessment

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KEYWORDS

Orthodontic appliance, Biodegradation, Nickel release, Chromium release, Atomic absorption spectrophotometry, Biocompatibility

ABSTRACT:

Background: Orthodontic appliances are routinely exposed to the oral environment for extended periods, raising concerns about metal ion release and potential systemic effects.

Objectives: This in vitro study aimed to compare the degradation of nickel and chromium from standard orthodontic appliances containing either stainless steel or nickel-titanium archwires in artificial saliva, and to assess whether released metal concentrations remain within biological limits.

Materials and Methods: Ten identical sets of orthodontic appliances simulating complete maxillary fixed appliances were used. Five sets were ligated with 0.016 × 0.016-inch stainless steel archwires and five with nickel-titanium archwires of identical dimensions. Each appliance was immersed in 100ml of artificial saliva (pH 6.75) and maintained at 37°C for 28 days. Metal ion release was measured at days 1, 7, 14, 21, and 28 using atomic absorption spectrophotometry.

Results: Nickel release peaked on day 7 for both archwire types (0.358 ± 0.013 ppm for stainless steel; 0.372 ± 0.013 ppm for nickel-titanium), while chromium release peaked on day 14 (0.156 ± 0.013 ppm for stainless steel; 0.152 ± 0.008 ppm for nickel-titanium). Total nickel release over 28 days was 1.266 ppm for stainless steel and 1.326 ppm for nickel-titanium appliances. Total chromium release was 0.526 ppm for stainless steel and 0.536 ppm for nickel-titanium. No statistically significant differences were observed between archwire types ($p > 0.05$).

Conclusion: Both stainless steel and nickel-titanium orthodontic appliances release nickel and chromium ions in artificial saliva, with release patterns showing temporal variation. The amounts released remain within established biological safety limits, though individual patient susceptibility should be considered.

1. Introduction

Orthodontic treatment involves prolonged exposure of metallic appliances to the complex oral environment, which presents unique challenges including temperature fluctuations, pH variations, enzymatic activity, and microbial colonization[1,2]. These factors contribute to corrosion and biodegradation of orthodontic components, resulting in metal ion release into surrounding tissues and systemic circulation[3]. Among released elements, nickel and chromium are of primary concern due to their prevalence in orthodontic alloys and documented potential for adverse biological effects[4,5].

Nickel comprises 8-12% of stainless steel and approximately 50% of nickel-titanium alloys commonly used in orthodontics. Epidemiological studies indicate that 10-15% of the population demonstrates nickel sensitivity, with higher prevalence among females[6]. Nickel has been implicated in hypersensitivity reactions ranging from localized oral mucositis to systemic allergic responses[7]. The International Agency for Research on Cancer has classified nickel as a possible human carcinogen, although evidence at orthodontic

exposure levels remains inconclusive. Chromium, constituting 17-20% of stainless steel alloys, exists in multiple oxidation states with varying biological effects Trivalent chromium is relatively benign and essential for glucose metabolism, while hexavalent chromium demonstrates cytotoxic and genotoxic properties. Corrosion in the oral environment may facilitate conversion between these oxidation states, raising toxicity concerns[8].

Biodegradation of orthodontic appliances occurs through chemical corrosion, electrochemical corrosion, and mechanically-assisted degradation. The oral environment's corrosive potential is enhanced by chloride ions, organic acids from bacterial metabolism, proteolytic enzymes in saliva, and dietary-associated pH fluctuations. Galvanic coupling between dissimilar metals accelerates corrosion through electrochemical mechanisms. Previous investigations have demonstrated measurable metal ion release both in vitro and in vivo, though considerable variability exists in reported rates due to differences in methodologies, alloy compositions, and environmental conditions[9]. Understanding metal release kinetics and magnitude is crucial for risk assessment and patient safety, particularly for individuals with metal sensitivities or requiring prolonged treatment.

Atomic absorption spectrophotometry offers excellent sensitivity, selectivity, and reproducibility for detecting trace metal concentrations, making it suitable for biocompatibility assessment. Despite extensive research, questions remain regarding comparative release profiles between different archwire materials and temporal dynamics under standardized conditions. This investigation was designed with specific objectives: first, to compare in vitro nickel and chromium release from standard orthodontic appliances with either stainless steel or nickel-titanium archwires; second, to assess temporal metal release patterns over 28 days simulating one month of clinical exposure; third, to quantify released metal concentrations using atomic absorption spectrophotometry and evaluate whether concentrations remain within biological safety limits; and fourth, to determine whether statistically significant differences exist between appliances with stainless steel versus nickel-titanium archwires[10].

2. Materials & Methods

Ten identical orthodontic appliance sets were fabricated, each simulating a complete maxillary fixed appliance with full dentition. Each set comprised two second molar bands, two first molar bands with welded buccal tubes (0.047×0.065 inches) and lingual buttons, two each of second premolar, first premolar, canine, lateral incisor, and central incisor edgewise brackets with mesh bases, pre-formed upper archwires (0.016×0.016 inches, 10.5 cm length), and ligature wire (0.010 inches diameter). All components were obtained from established manufacturers and used as-received. Bands were manufactured from AISI Type 305 stainless steel (T.P. Orthodontics, USA), buccal tubes from Type 316 stainless steel (Dentaurum, Germany), brackets from Type 303 and 304 stainless steel (Dentaurum, Germany), and archwires from either stainless steel or nickel-titanium (Dentaurum, Germany).

Appliances were constructed on a standard typodont ensuring consistent positioning. Five sets were ligated with stainless steel archwires and five with nickel-titanium archwires. Small bends were placed at archwire ends to prevent band displacement. Band inner surfaces and bracket bases were deliberately left uncoated to eliminate extraneous nickel and chromium sources from cements or bonding materials. This approach resulted in exposed surface area approximately double that encountered clinically, representing a conservative maximum estimate equivalent to full maxillary and mandibular appliances.

Modified artificial saliva based on Gjerdet and Hero's formulation[11] was prepared containing sodium chloride (0.4 g), potassium chloride (1.21 g), sodium phosphate dibasic dihydrate (0.78 g), sodium sulfide nonahydrate (0.005 g), and urea (1 g) in 1000 ml distilled deionized water. Calcium chloride was replaced with equivalent potassium chloride to prevent precipitation. All measurements used electronic analytical balance for precision. Egg-derived albumin was initially considered but excluded due to high endogenous nickel concentration. The pH was adjusted to 6.75±0.15 using 10 N sodium hydroxide added in 50 µl increments, simulating neutral to slightly acidic oral conditions[1].

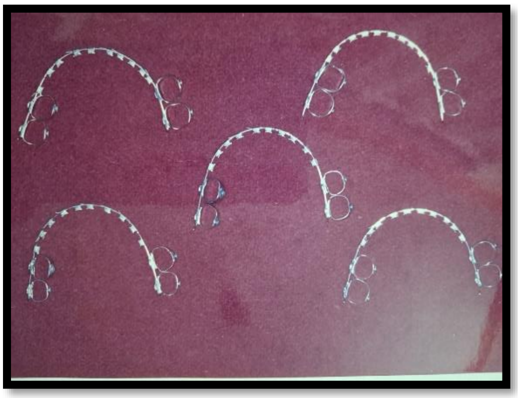

Fig 1: Orthodontic appliances used in the study

Each appliance was placed in separate glass bottles containing 100 ml fresh artificial saliva. Bottles were maintained at 37°C in an environmental incubator throughout the 28-day period. On days 1, 7, 14, 21, and 28, entire saliva volumes were removed and replaced with fresh solution, except day 28 when the experiment concluded. This protocol prevented saturation with corrosion products that could inhibit further release[13].

All glassware was cleaned with 1:1:1 solution of sulfuric acid, nitric acid, and deionized water, rinsed thrice with deionized water, and air-dried to eliminate metal contamination. Metal analysis used atomic absorption spectrophotometer Model 1800 (Hitachi). This technique exploits unique elemental absorption spectra, with element-specific wavelengths generated by hollow cathode lamps and absorbed by analyte vapor clouds proportionally to concentration. Commercially available nickel and chromium standards prepared working standards through serial dilution.

The analytical protocol involved multiple steps for accuracy. A 20 ml nickel standard (4 ppm) established calibration curves. For samples, 10 ml nickel standard was added to 10 ml test saliva. Initial measurements showed drastic reduction indicating dilution from deionized water. To correct this, 10 ml nickel standard was added to 10 ml deionized water and analyzed. Released nickel was calculated as the difference between standard with saliva and standard with deionized water. Each sample was analyzed in triplicate for mean values. Identical procedures used 5 ppm chromium standards. Post-experiment, appliances were examined under stereomicroscope for corrosion products.

Statistical analysis included descriptive statistics (mean, standard deviation, standard error, range), one-way ANOVA to determine temporal differences within groups, studentized range test for post-hoc analysis identifying specific significant time points, and median test with Fisher's exact probability comparing archwire types. Significance was established at α=0.05.

3. Results

The investigation generated 50 samples (25 per archwire type) across five time points, revealing distinct temporal patterns with high statistical significance. Nickel release from stainless steel appliances showed temporal variation with day 1 mean of 0.152±0.008 ppm (range 0.14-0.16), peak day 7 at 0.358±0.013 ppm (range 0.35-0.37), day 14 at 0.300±0.016 ppm (range 0.28-0.31), day 21 at 0.256±0.015 ppm (range 0.24-0.27), and day 28 at 0.200±0.016 ppm (range 0.18-0.22). ANOVA showed highly significant differences (F=163.7, $p<0.001$) with minimal significant range of 0.03 ppm. All pairwise comparisons between time points were significant. Total 28-day nickel release was 1.266 ppm (0.045 ppm/day average).

Nickel-titanium appliances showed similar patterns with day 1 at 0.166±0.021 ppm (range 0.14-0.19), peak day 7 at 0.372±0.013 ppm (range 0.36-0.39), day 14 at 0.316±0.012 ppm (range 0.29-0.34), day 21 at 0.268±0.018 ppm (range 0.25-0.29), and day 28 at 0.209±0.011 ppm (range 0.19-0.22). Statistical analysis revealed highly significant

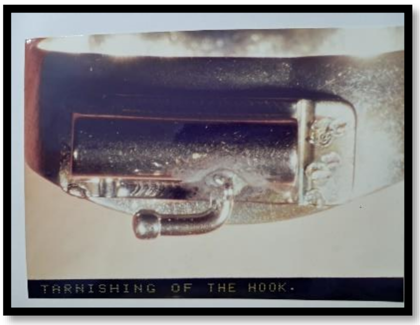

Fig 2: Surface corrosion around the soldered joint between hook and tube

Fig 3: Surface carrion around the lingual button on the band.

Fig 4: Surfaces corrosion at the brackets – mesh base junction

temporal variation (F=350.0, $p<0.001$) with minimal significant range of 0.02 ppm. All temporal comparisons were significant. Total release was 1.326 ppm (0.047 ppm/day average).

Chromium release from stainless steel appliances peaked later, with day 1 at 0.058±0.013 ppm (range 0.04-0.07), day 7 at 0.102±0.008 ppm (range 0.09-0.11), peak day 14 at 0.156±0.013 ppm (range 0.14-0.17), day 21 at 0.114±0.011 ppm (range 0.10-0.13), and day 28 at 0.096±0.011 ppm (range 0.08-0.11). ANOVA indicated significant variation (F=53.0, $p<0.001$) with minimal significant range 0.02 ppm. Significant differences existed between day 1 and subsequent days, day 7 and day 14, and day 14 versus days 21 and 28. Total release was 0.526 ppm (0.019 ppm/day).

Nickel-titanium chromium release showed day 1 at 0.066±0.005 ppm (range 0.06-0.07), day 7 at 0.112±0.008 ppm (range 0.10-0.12), peak day 14 at 0.152±0.008 ppm (range 0.14-0.16), day 21 at 0.116±0.015 ppm (range 0.10-0.14), and day 28 at 0.090±0.010 ppm (range 0.08-0.10). Analysis revealed significant variation (F=52.5, $p<0.001$) with minimal significant range 0.02 ppm. Total release was 0.536 ppm (0.019 ppm/day).

Comparative analysis showed no significant differences in nickel release between archwire types at any time point. Day 1: stainless steel 0.152±0.008 ppm versus nickel-titanium 0.166±0.021 ppm; day 7: 0.358±0.013 versus 0.372±0.013; day 14: 0.300±0.016 versus 0.316±0.021; day 21: 0.256±0.015 versus 0.268±0.018; day 28: 0.200±0.016 versus 0.204±0.011. Median test yielded $p=0.39$, confirming no significant differences. Similarly, chromium release showed no significant differences between types at any time point (p values ranging 0.08-0.55, overall $p=0.39$). Stereomicroscopic examination revealed visible corrosion products on component surfaces varying by location and component type.

Arch wire	Metal ion	Day	Range (ppm)	Mean (ppm)	SD	SE	F Value*	p-value	Min. Sig. Range	Significance of Difference in Ion Release at Different Time Intervals
Stainless Steel	Nickel	1	0.14–0.16	0.152	0.008	0.003	163.7	p < 0.001	0.03	1 α 7, 14, 21, 28 – Significant
		7	0.35–0.37	0.358	0.013	0.006				7 α 14, 21, 28 – Significant
		14	0.28–0.31	0.300	0.016	0.007				14 α 21, 28 -Significant
		21	0.24–0.27	0.256	0.015	0.007				21 α 28 – Significant
		28	0.18–0.22	0.200	0.016	0.007				
Nickel–Titanium	Nickel	1	0.14–0.19	0.166	0.021	0.009	350.0	p < 0.001	0.02	1 α 7, 14, 21, 28 – Significant
		7	0.36–0.39	0.372	0.013	0.006				7 α 14, 21, 28 – Significant
		14	0.29–0.34	0.316	0.012	0.009				14 α 21, 28 -Significant
		21	0.25–0.29	0.268	0.018	0.008				21 α 28 – Significant
		28	0.19–0.22	0.209	0.011	0.005				
Stainless Steel	Chromium	1	0.04–0.07	0.058	0.013	0.006	53.0	p < 0.001	0.02	1 α 7, 14, 21, 28 – Significant
		7	0.09–0.11	0.102	0.008	0.003				7 α 14 – Significant
		14	0.14–0.17	0.156	0.013	0.006				14 α 21, 28 -Significant
		21	0.10–0.13	0.114	0.011	0.005				
		28	0.08–0.11	0.096	0.011	0.005				
Nickel–Titanium	Chromium	1	0.06–0.07	0.066	0.005	0.002	52.5	p < 0.001	0.02	1 α 7, 14, 21, 28 – Significant
		7	0.10–0.12	0.112	0.008	0.004				7 α 14, 28 – Significant
		14	0.14–0.16	0.152	0.008	0.004				14 α 21, 28 -Significant
		21	0.10–0.14	0.116	0.015	0.007				21 α 28 – Significant
		28	0.08–0.10	0.090	0.010	0.004				

*Analysis of variance,** Studentized range test

Table I. Comparative Analysis of Nickel and Chromium Ion Release (ppm) from Orthodontic Appliances Ligated with Stainless Steel and Nickel–Titanium Archwires over 28 Days

Day	Archwire Type	Nickel Release Mean (ppm)	Standard Deviation (SD)	Significance	Mean Chromium Release (ppm)	Standard Deviation (SD)	Significance

1	SS	0.152	0.008	NS	0.058	0.013	NS (p = 0.39)
	NiTi	0.166	0.021		0.066	0.005	
7	SS	0.358	0.013	NS	0.102	0.008	NS (p = 0.08)
	NiTi	0.372	0.013		0.112	0.008	
14	SS	0.300	0.016	NS	0.156	0.013	NS (p = 0.55)
	NiTi	0.316	0.021		0.152	0.008	
21	SS	0.256	0.015	NS	0.114	0.011	NS (p = 0.24)
	NiTi	0.268	0.018		0.116	0.015	
28	SS	0.200	0.016	NS	0.096	0.011	NS (p = 0.39)
	NiTi	0.204	0.011		0.090	0.010	

*Median test – Fisher's exact probability (p=0.39),NS: Non-significant at alpha = 0.05

Table II: Comparative statistics for the rate of nickel and chromium release on days 1,7,14,21, & 28 between appliances ligated with Stainless Steel & Nickel titanium archwires

4. Discussion

This investigation provides comprehensive data on temporal nickel and chromium release from orthodontic appliances with stainless steel or nickel-titanium archwires. Both appliance types release measurable metal quantities in artificial saliva under simulated oral conditions with distinct patterns for each element. Nickel release peaking on day 7 for both types reflects characteristic biphasic patterns consistent with previous research[14,15]. Elevated initial release likely represents superficial oxide layer removal and degradation of previously unexposed metal surfaces, as manufacturing and storage leave surfaces in reactive states promoting rapid initial release. Subsequent decline suggests stable passive oxide film formation on exposed surfaces, with protective layers primarily of chromium oxide and nickel oxide reducing continued corrosion by serving as diffusion barriers.

Peak nickel values of 0.358 ppm for stainless steel and 0.372 ppm for nickel-titanium fall within previously reported ranges. Barrett et al[16] reported 0.01-0.30 ppm from various archwires, while Kerosuo et al.[17] observed higher values reaching 1.8 ppm under pH cycling with enzymatic challenge. Variations across studies reflect differences in surface area exposure, solution composition, temperature control, and measurement techniques. Chromium release peaking on day 14 for both types suggests different corrosion mechanisms than nickel. Stainless steel passive films are predominantly chromium oxide-rich, requiring extensive degradation before significant release. Initial corrosion may preferentially release nickel, with chromium accessible only after substantial film disruption. Additionally, chromium exhibits nobler electrochemical behavior than nickel, with nickel potentially acting as sacrificial anode in galvanic couples, delaying chromium release. Chromium values approximately 0.15 ppm peak are considerably lower than nickel, consistent with chromium's greater corrosion resistance and structural role in passive film integrity, aligning with Hwang et al.[18] findings.

The absence of significant differences between archwire types warrants consideration. While nickel-titanium contains approximately 50% nickel versus 8-12% in stainless steel, total nickel-titanium archwire surface area represents only a fraction of complete appliance systems. Bands, brackets, and tubes contribute substantially to total release, potentially overshadowing archwire composition differences. Furthermore, nickel-titanium alloys possess highly stable titanium oxide surface films effectively protecting against corrosion, compensating for higher nickel content and yielding comparable release rates. Galvanic coupling between dissimilar metals creates complex electrochemical interactions potentially reducing

apparent differences. The experimental design leaving band and bracket surfaces uncoated, necessary for eliminating extraneous metal sources, resulted in exposed areas considerably exceeding clinical situations, potentially amplifying band and bracket contributions and obscuring archwire-specific differences. Previous comparative studies yielded variable results, with some reporting higher nickel release from isolated nickel-titanium versus stainless steel archwires[19, 20], while others found no significant differences[21], particularly when evaluating complete systems.

Evaluating biological significance requires considering established safety thresholds. The World Health Organization established tolerable daily intake for nickel at 0.1-0.2 mg/day for 60 kg individuals, while the European Food Safety Authority set 0.13 mg/day. Peak daily nickel release of approximately 0.372 ppm from 100 ml equals 0.0372 mg/day experimentally. Considering humans produce 0.5-1.5 liters saliva daily and assuming complete dissolution and absorption, estimated daily exposure would range 0.186-0.558 mg. While approaching or slightly exceeding tolerable daily intake values, several factors suggest lower actual exposure: the experimental design intentionally maximized exposed surface area, not all released metal is absorbed systemically, salivary clearance and swallowing reduce local concentrations, and binding to salivary proteins and dietary components limits bioavailability.[22]

Peak daily chromium release of approximately 0.156 ppm or 0.0156 mg in 100 ml corresponds to estimated daily exposure of 0.078-0.234 mg based on normal salivary flow. These values fall below WHO acceptable daily intake for trivalent chromium of 0.5-1.0 mg/day for 60 kg individuals, though concerns remain regarding potential conversion to hexavalent chromium under specific oral conditions.[23]

Clinical implications include the importance of obtaining comprehensive medical histories with previous metal allergies before appliance placement. Patients with known nickel allergy may benefit from alternative designs, though this study suggests alternatives may not dramatically reduce total exposure considering entire appliance systems. Minimizing exposed metal surface area through appropriate cements and bonding materials may reduce release, though protective effects require validation. Patients should be monitored for metal sensitivity signs including oral mucositis, gingival inflammation, or systemic manifestations, allowing timely intervention. While no significant difference existed between archwire types, individual patient factors may influence material selection. Alternative alloys including titanium-molybdenum and beta-titanium offer potential advantages for sensitive patients, though presenting their own clinical considerations [24]

Conclusion

This investigation demonstrates both stainless steel and nickel-titanium orthodontic appliances release measurable nickel and chromium quantities in artificial saliva under simulated oral conditions. Nickel release exhibits biphasic patterns with peak release on day 7, averaging 0.358 ppm for stainless steel and 0.372 ppm for nickel-titanium, followed by progressive decline through day 28. Chromium release shows distinct temporal patterns with delayed peaks on day 14, averaging 0.156 ppm for stainless steel and 0.152 ppm for nickel-titanium. Total 28-day nickel release was 1.266 ppm for stainless steel and 1.326 ppm for nickel-titanium, while chromium release was 0.526 ppm and 0.536 ppm respectively. No statistically significant differences in metal release existed between appliances with stainless steel versus nickel-titanium archwires at any time point.

Released amounts approach but generally remain within established biological safety limits when corrected for clinical surface area and considering incomplete systemic absorption. However, the conservative experimental design maximizing exposed metal surfaces suggests actual clinical exposure may be lower. The temporal dynamics with nickel peaking early and chromium later provide insights into maximal patient exposure

timing during treatment. These findings support continued use of both appliance types for general populations while emphasizing thorough medical history evaluation and patient monitoring, particularly for individuals with known metal sensitivities. Appliance selection should primarily consider mechanical and clinical factors rather than differential metal release concerns, except in documented hypersensitivity cases. Clinicians should maintain vigilance during the first two weeks when release rates peak and recognize potential adverse reactions promptly.

Limitations

Several limitations merit acknowledgment. The in vitro design using artificial saliva cannot fully replicate the complex oral environment including mucins, immunoglobulins, enzymes, microbial colonization producing organic acids, and pH fluctuations. Constant 37°C temperature maintenance did not simulate thermal challenges from food and beverage consumption affecting corrosion kinetics. Leaving band and bracket surfaces uncoated, while eliminating extraneous metal sources, resulted in exposed areas approximately double clinical situations, likely overestimating actual exposure. Complete saliva replacement at intervals prevented saturation but also prevented equilibrium establishment that might occur clinically (54). Static immersion eliminated mechanical stresses including fretting corrosion, stress corrosion cracking, and mechanically-assisted degradation ubiquitous clinically from masticatory forces, brushing, and tongue movement. The 28-day duration, while representing substantial adjustment intervals, is considerably shorter than typical 18–36 month treatment durations, with long-term studies needed to determine whether declining rates continue or mechanical disruption causes repeated peaks. Dietary factors including acidic beverage consumption and citrus fruits causing pH fluctuations were not simulated . Individual variations in salivary composition, flow rate, buffering capacity, and pH known to influence corrosion were not addressed by standardized artificial saliva. Atomic absorption spectrophotometry provides total metal concentrations but not speciation information distinguishing between chromium oxidation states with different toxicological implications. Sample size of five appliances per group, while adequate for detecting observed trends, may have limited power for detecting smaller differences. The study represented one bracket prescription from specific manufacturers, with generalizability requiring evaluation of multiple manufacturers and designs. Future investigations should incorporate mechanical cycling, dietary challenges, longer durations, in vivo validation, and multi-element analysis to provide more complete understanding of orthodontic appliance biocompatibility and safety across diverse patient populations under varied clinical conditions.

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