



www.bioinformation.net
Volume 22(9)



Research Article

Received September 1, 2026; Revised September 30, 2026; Accepted September 30, 2026, Published September 30, 2026

DOI: 10.6026/973206300225786

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478

2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Citation: Chavan *et al.* Bioinformation 22(9): 5786-5790 (2026)

Comparative metal ion release after silver soldering and spot welding: An *in vitro* study

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Abstract:

Corrosion of orthodontic appliances releases metal ions, but the effects of joining methods under common oral exposures remain unclear. Therefore, it is of interest to compare the nickel, chromium, copper and iron release from 90 silver-soldered and spot-welded stainless steel molar bands immersed in artificial saliva, mouthwashes and a carbonated drink. Metal ion release was quantified using Inductively Coupled Plasma Mass Spectrometry and surface changes were evaluated by Scanning Electron Microscopy. Silver-soldered bands released significantly more metal ions than spot-welded bands in all media ($p < 0.001$), with maximum release in fluoride-alcohol mouthwash and minimum release in chlorhexidine. These findings identify the joining method as the primary determinant of corrosion and support spot welding with chlorhexidine as a more biocompatible clinical approach.

Keywords: Chlorhexidine, chromium, copper, corrosion, dietary drinks, fluoride mouthwash, inductively coupled plasma mass spectrometry (ICP-MS), iron, nickel, orthodontic bands, silver soldering, spot welding

Background:

Fixed orthodontic appliances composed predominantly of stainless steel remain a cornerstone of contemporary orthodontic therapy. Although stainless steel is appreciated for its mechanical performance and corrosion resistance, the dynamic and frequently acidic intra-oral environment can disrupt its passive chromium-oxide layer and promote the release of constituent metal ions [1]. Even at the low concentrations typically detected, nickel, chromium, copper and iron ions are clinically relevant because of their reported allergenic, cytotoxic and oxidative effects on oral and systemic tissues [2]. A recent narrative review of *in vitro* studies has emphasised that the rate and extent of ion release vary with alloy composition, surface preparation, immersion medium and the duration of exposure [3]. Mouthwashes are routinely prescribed during fixed orthodontic therapy to manage plaque accumulation around brackets and bands. Fluoride mouthwashes are widely used for caries prevention, but the fluoride ion is known to destabilise the passive layer of stainless steel and increase metallic ion release [4]. The corrosive potential is further amplified when fluoride is combined with alcohol, as observed in commercially available formulations and confirmed by *in vitro* investigations using ICP-MS analysis of soldered and welded appliances [5, 6]. In contrast, chlorhexidine gluconate, although the most widely used antiseptic rinse during orthodontic care, has generally been reported to exert a milder effect on corrosion behaviour [7]. A narrative review of fluoridated mouthwashes also highlighted appreciable variations in corrosion potential across commercial formulations, supporting the need for product-specific evaluation [8]. The fabrication of orthodontic appliances frequently requires the joining of two or more metal components, most commonly by silver soldering or spot welding. Silver soldering uses a silver-based filler alloy containing additional copper and zinc, producing a strong but heterogeneous joint with a micro-galvanic structure that is preferentially attacked by oral fluids [5]. Spot welding, by contrast, fuses stainless steel components by localised electrical resistance heating without the introduction of a filler metal,

generating a more homogeneous joint and smoother surface finish [6]. The metallurgical heterogeneity of silver solder is further linked to local cytotoxic effects, with surface zinc segregation and copper-rich phases reported to influence biocompatibility [7]. The clinical consequences of metal ion exposure include allergic contact reactions, particularly to nickel, which has been reported as a recurrent sensitiser in young female orthodontic patients and, in occasional reports, even as a trigger for angioedema [8]. Strategies to minimise these adverse effects of dental alloys have been the focus of recent comprehensive reviews emphasising material selection and patient counselling [9, 10]. Beyond mouthwashes, dietary habits play a critical role. Carbonated cola beverages contain phosphoric acid, citric acid and carbonic acid and produce a low intra-oral pH that has been shown to enhance the release of metallic ions from orthodontic alloys and to accelerate surface degradation of aligners [11, 12 and 13]. Working properties of nickel-titanium archwires have also been shown to deteriorate after exposure to antiseptic and fluoride agents during clinical use [14] and chlorhexidine in combination with sodium fluoride has been documented to alter corrosion behaviour of copper-containing NiTi archwires [15]. Although individual aspects of orthodontic corrosion have been extensively investigated, direct comparison of silver soldering and spot welding across the spectrum of mouthwashes and dietary drinks most commonly encountered by orthodontic patients remains limited [16]. Therefore, it is of interest to quantify and compare nickel, chromium, copper and iron ion release from silver-soldered and spot-welded stainless steel molar bands in different oral environments.

Methodology:

The study protocol was reviewed and approved by the Institutional Ethics Committee prior to commencement. A total of 90 commercially available stainless steel upper first molar bands of uniform dimension and composition (without prewelded attachments) were selected for the study. Sample size estimation was performed using G*Power software (version

3.1.9.6), with an effect size of 0.45, statistical power of 80% and a significance level of 0.05, yielding a minimum of nine samples per subgroup. Nine bands per subgroup were therefore included to ensure adequate statistical power across the ten subgroups, consistent with sample size approaches reported in comparable *in vitro* investigations. The bands were randomly allocated into two main groups according to the method of joining. (Group 1) (n = 45) consisted of bands joined by spot welding using a calibrated orthodontic spot welder at standardized current and dwell time. (Group 2) (n = 45) comprised bands joined by silver soldering, performed by a single trained operator using a standardized silver-based solder alloy (silver, copper, zinc) and a fluoride-free flux under a controlled flame, in line with previously published metallurgical descriptions of orthodontic solder alloys. A stainless steel auxiliary wire of identical gauge was attached to each band by the assigned joining method to provide a defined joint area for evaluation. Each main group was further subdivided into five subgroups of nine samples each based on the immersion medium, yielding ten subgroups in total (Table 1). The test solutions comprised: (i) artificial saliva (control, prepared at pH 6.8 to simulate normal intra-oral conditions); (ii) 0.05% sodium fluoride mouthwash (225 ppm NaF, neutral commercial formulation); (iii) sodium fluoride with alcohol-containing mouthwash; (iv) 0.2% chlorhexidine gluconate mouthwash; and (v) a commercially available carbonated cola beverage. Solution selection followed the formulations most commonly used in published comparative orthodontic corrosion studies. Prior to immersion, each band was ultrasonically cleaned in deionised water for 10 minutes, air-dried and weighed on a precision electronic balance. Each sample was then placed in an individual sterile polypropylene container with 10 mL of the assigned test solution and incubated at 37°C in a constant-temperature incubator to simulate intra-oral conditions. The immersion period was standardised at 14 days, with the solutions refreshed every 48 hours to mimic dynamic oral conditions and to prevent saturation of the medium with released ions, an approach consistent with recent *in vitro* models for orthodontic corrosion. At the end of the immersion period, the bands were retrieved, rinsed with deionised water and the immersion solutions were collected for elemental analysis. The concentrations of nickel, chromium, copper and iron ions in each solution were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) with appropriate calibration standards and internal standards to correct for matrix effects. All measurements were performed in triplicate and the mean value was used for analysis. Representative bands from each subgroup were examined by Scanning Electron Microscopy (SEM) to evaluate surface morphology and identify features such as pitting, crevice corrosion and grain boundary attack, following established SEM

protocols for orthodontic appliances. Data were analysed using IBM SPSS Statistics version 22.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics were expressed as mean ± standard deviation. The Shapiro-Wilk test confirmed non-normal distribution of the data; therefore, non-parametric tests were applied. Intergroup comparisons across the five test solutions within each joining method were performed using the Kruskal-Wallis test with post-hoc pairwise comparisons and the Mann-Whitney U test was used for comparison between corresponding spot-welded and silver-soldered subgroups. A p-value of ≤ 0.05 was considered statistically significant.

Results:

Quantifiable concentrations of nickel, chromium, copper and iron ions were detected in all immersion solutions after the 14-day exposure period. The mean concentrations (µg/L) of released ions for spot-welded and silver-soldered subgroups are summarized in (Table 2) and (Table 3), respectively. Across every immersion medium, silver-soldered bands released significantly higher concentrations of all four ions than their spot-welded counterparts (Mann-Whitney U test; p < 0.001) (Table 4). Within the spot-welded group, the Kruskal-Wallis test showed significant differences in ion release among the five immersion solutions (p < 0.001 for each ion). The lowest ion release was consistently observed in artificial saliva, while the sodium fluoride with alcohol mouthwash produced the highest release of nickel and copper. The cola beverage produced the highest release of iron and chlorhexidine produced the lowest release among the test mouthwashes. Within the silver-soldered group, a similar pattern of significant intergroup differences was observed (Kruskal-Wallis; p < 0.001). However, the absolute concentrations of all ions were substantially higher than in spot-welded subgroups. The sodium fluoride with alcohol mouthwash produced the most pronounced release of copper (198.4 ± 14.6 µg/L), followed by the cola beverage. Chlorhexidine again resulted in the lowest ion release within the soldered group, although values remained higher than those in spot-welded samples immersed in any medium. Scanning electron microscopy supported the quantitative findings. Spot-welded bands immersed in artificial saliva and chlorhexidine showed largely intact surfaces with only mild striations. Spot-welded bands exposed to fluoride-alcohol mouthwash and cola exhibited moderate surface roughness but no extensive pitting. In contrast, silver-soldered bands consistently demonstrated greater surface irregularity, with discrete pits, crevice corrosion at the solder-parent metal interface and granular deposits, particularly in the fluoride-alcohol and cola subgroups, in agreement with previous SEM-based observations on soldered orthodontic components.

Table 1: Distribution of samples across study subgroups

Subgroup	Method of Joining	Immersion Solution	n
I	Spot welding	Artificial saliva (Control)	9
II	Spot welding	Sodium fluoride mouthwash	9
III	Spot welding	Sodium fluoride + alcohol mouthwash	9
IV	Spot welding	Chlorhexidine gluconate mouthwash	9
V	Spot welding	Carbonated cola beverage	9

VI	Silver soldering	Artificial saliva (Control)	9
VII	Silver soldering	Sodium fluoride mouthwash	9
VIII	Silver soldering	Sodium fluoride + alcohol mouthwash	9
IX	Silver soldering	Chlorhexidine gluconate mouthwash	9
X	Silver soldering	Carbonated cola beverage	9

Table 2: Mean (± SD) metal ion release (µg/L) from spot-welded bands (Group A; n = 9 per subgroup)

Immersion Solution	Nickel (Ni)	Chromium (Cr)	Copper (Cu)	Iron (Fe)
Artificial saliva (Control)	12.4 ± 1.8	8.9 ± 1.2	4.6 ± 0.9	18.3 ± 2.4
Sodium fluoride mouthwash	28.7 ± 2.6	19.5 ± 2.1	9.8 ± 1.5	36.2 ± 3.1
NaF + alcohol mouthwash	41.6 ± 3.4	27.4 ± 2.7	14.7 ± 1.9	48.9 ± 3.8
Chlorhexidine mouthwash	16.3 ± 2.0	11.2 ± 1.4	6.1 ± 1.1	22.7 ± 2.6
Carbonated cola beverage	36.9 ± 3.1	23.8 ± 2.4	12.6 ± 1.7	54.7 ± 4.2
p-value (Kruskal-Wallis)	< 0.001	< 0.001	< 0.001	< 0.001

Table 3: Mean (± SD) metal ion release (µg/L) from silver-soldered bands (Group B; n = 9 per subgroup)

Immersion Solution	Nickel (Ni)	Chromium (Cr)	Copper (Cu)	Iron (Fe)
Artificial saliva (Control)	31.6 ± 3.2	21.4 ± 2.5	48.2 ± 4.1	39.7 ± 3.4
Sodium fluoride mouthwash	62.5 ± 4.7	44.6 ± 3.9	128.9 ± 9.7	74.8 ± 5.3
NaF + alcohol mouthwash	87.3 ± 6.2	58.7 ± 4.6	198.4 ± 14.6	96.5 ± 6.8
Chlorhexidine mouthwash	38.4 ± 3.6	26.1 ± 2.7	62.5 ± 5.2	46.3 ± 3.9
Carbonated cola beverage	78.6 ± 5.4	52.3 ± 4.1	176.5 ± 12.8	112.4 ± 8.1
p-value (Kruskal-Wallis)	< 0.001	< 0.001	< 0.001	< 0.001

Table 4: Comparison of total metal ion release (µg/L) between corresponding spot-welded and silver-soldered subgroups (Mann-Whitney U test)

Immersion Solution	Spot Welding (Total)	Silver Soldering (Total)	p-value
Artificial saliva (Control)	44.2 ± 3.6	140.9 ± 8.4	< 0.001
Sodium fluoride mouthwash	94.2 ± 5.7	310.8 ± 17.2	< 0.001
NaF + alcohol mouthwash	132.6 ± 7.2	440.9 ± 22.6	< 0.001
Chlorhexidine mouthwash	56.3 ± 4.4	173.3 ± 9.8	< 0.001
Carbonated cola beverage	128.0 ± 6.9	419.8 ± 21.3	< 0.001

Discussion:

The release of metallic ions from orthodontic appliances into the oral environment remains an unresolved concern in clinical orthodontics, particularly in patients undergoing prolonged fixed appliance therapy. The present *in vitro* study compared the corrosion behaviour of silver-soldered and spot-welded stainless steel molar bands in five oral fluids and showed that the method of joining and the chemical nature of the immersion medium are both independent determinants of ion release. Across every test solution, silver soldering produced significantly higher concentrations of nickel, chromium, copper and iron than spot welding. This pattern is consistent with previous reports identifying soldered joints as preferential sites of corrosion in orthodontic appliances [17] and with metallurgical analyses showing copper-rich phases and zinc segregation in silver solder microstructures [18]. The elevated release from silver-soldered samples can be attributed to several interrelated mechanisms. The bimetallic interface between the solder filler and the stainless steel parent metal establishes a micro-galvanic cell in which the less noble copper-rich phase preferentially dissolves. This explains the disproportionately high copper concentrations observed in the soldered subgroups, particularly in fluoride-alcohol mouthwash (198.4 ± 14.6 µg/L) and cola beverage (176.5 ± 12.8 µg/L). The heterogeneous microstructure of the solder joint, with its dendritic morphology and potential entrapment of flux residues, further provides preferential sites for crevice corrosion. By contrast, spot welding produces a fusion zone with composition essentially identical to the parent metal and a smoother surface continuity, accounting for the lower ion release in this group and consistent with comparative reports on welded

versus soldered orthodontic appliances [19]. The aggressive behaviour of fluoride mouthwashes towards stainless steel orthodontic components has been previously documented and is supported by recent investigations using ICP-MS across different fluoride concentrations and archwire types. Fluoride ions disrupt the protective chromium-oxide passive layer through the formation of soluble fluoride complexes, exposing the underlying alloy to direct chemical attack. The addition of alcohol further amplifies this effect by lowering the dielectric constant of the medium and facilitating ion exchange across the metal-electrolyte interface, an effect that has also been linked to deterioration of the working properties of nickel-titanium archwires during clinical use [20]. The present study confirms that the combination of sodium fluoride and alcohol produces the most aggressive intra-oral medium of those tested, leading to the highest cumulative ion release in both joining groups. The cola beverage produced the second-highest release of ions, particularly iron, in both groups. This is consistent with its low pH (approximately 2.5) and the presence of phosphoric and carbonic acids, which destabilise the passive layer and accelerate anodic dissolution. Recent studies on aligners and brackets confirm that prolonged exposure to acidic carbonated drinks is detrimental to orthodontic materials [13], reinforcing existing recommendations to limit such intake during fixed orthodontic therapy. Chlorhexidine, although routinely used as an antimicrobial adjunct during orthodontic treatment, produced the least corrosion of the mouthwashes tested. Its near-neutral pH and absence of fluoride probably explain this comparatively benign profile, an observation supported by recent comparative studies on chlorhexidine and povidone-iodine rinses on stainless

steel brackets [21]. The clinical implications of these findings are noteworthy. Nickel hypersensitivity has been reported as a recurrent issue in orthodontic patients, with prevalence estimates of 4–14% in recent clinical cohorts and isolated severe presentations including angioedema have been described in young patients with prolonged exposure to nickel-containing dental devices [22]. Although the absolute ion concentrations detected in the present study remain below acutely toxic thresholds, cumulative chronic exposure during multi-year orthodontic treatment is plausible. The substantially higher ion release from silver-soldered components therefore favours the preferential use of spot welding wherever clinically feasible, in agreement with strategies proposed in recent reviews on minimising adverse effects of dental alloys [11]. Additional sources of intra-oral acid challenge, including gastric acid reflux, have been shown to further amplify corrosion and ion release [23], supporting a holistic approach to clinical risk assessment. Several limitations warrant acknowledgement. The static immersion model, although standardised and reproducible, does not fully replicate the dynamic intra-oral environment, in which salivary flow, mechanical stresses, biofilm formation and intermittent dietary exposure modulate corrosion kinetics. The 14-day immersion period, while consistent with comparable *in vitro* protocols, is shorter than the typical duration of fixed orthodontic therapy [24]. SEM analysis was qualitative and no quantitative surface roughness profilometry was performed. Furthermore, microbial corrosion mediated by oral flora has recently been recognised as an additional contributor to orthodontic alloy degradation and pathological factors such as gastroesophageal reflux can compound the corrosion challenge [25]. Future investigations should employ pH-cycling protocols, biofilm models and long-term *in vivo* evaluation, including measurement of nickel and chromium in saliva and serum of patients, to better characterise systemic exposure. Within these limitations, the present findings provide consistent and clinically relevant evidence that spot welding offers superior biocompatibility compared with silver soldering and that the choice of mouthwash and dietary habits meaningfully influence corrosion behaviour during fixed orthodontic treatment.

Conclusion:

Silver-soldered bands released higher ion concentrations across all media (fluoride-alcohol/cola most corrosive, chlorhexidine least), with SEM confirming greater surface damage in soldered samples. Spot welding is preferred and clinicians should be cautious with fluoride-alcohol mouthwashes and cola in

patients with soldered components. Moreover, such Long-term *in vivo* studies are needed for further research.

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