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Electroanalysis of nickel ions released in artificial saliva from three orthodontic arch wires: Stainless Steel (SS), NiTi, and CuNiTi

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***Abstract*---**Background: Nickel titanium wires are superior for first alignment because they have exceptional shape memory and super-elasticity. Increased concerns have been raised about the high rate of nickel (Ni) allergy and the growing usage of dental biomaterials that contain Ni. Aim: The aim of the study was to analyze and evaluate the rate of nickel release from different types of orthodontic arch wires. Materials and methods: A set of arch wires of nickel titanium (NiTi), SS and Cu-NiTi were immersed in artificial saliva for three days and analyzed after three days. The amount of Ni ions released from the sample were evaluated using electrochemical techniques such as Cyclic Voltammetry (CV), Electrochemical Impedance Spectroscopy (EIS) and polarization (Tafel) plot. Results: The EIS and Tafel graph confirmed the s-NiTi, s-CuNiTi showed an excellent corrosion resistance than the s-SS. From all the above measurements, we can

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conclude that the saliva can affect the corrosion resistance property of the SS, NiTi, CuNiTi day by day. Conclusion: From this study it was concluded that the saliva can affect the corrosion resistance property of the SS, NiTi, CuNiTi day by day, and there was nickel ion release but at a very negligible rate.

***Keywords*---**Nickel ions, Titanium, Arch wires, Orthodontics, EIS, Tafel plot, Ions.

1. Introduction

Dentistry's primary goal is to maintain or enhance the patient's quality of life by preventing diseases, treating pain, and enhancing phonetics, aesthetics, and/or masticatory efficiency. One of the key criteria for assessing the biological response and potential harm to cells and tissues associated with the usage of such materials is toxicity. There have been worries about metallic orthodontic appliances causing nickel allergy sufferers to react hypersensitivity [1]. There have been sporadic reports of negative reactions. Nickel is one of the basic elements and because it is simple to mix with other metals to create alloys, it is metal that is frequently used in orthodontic treatments [2]. Numerous orthodontic appliances' parts, such as stainless steel and nickel-titanium (NiTi) arch wires, brackets, bands, face bows, stainless steel ligatures, and stainless-steel parts of detachable appliances, are possible nickel sources [3]. Although ionic release in vivo in the oral cavity is more challenging to demonstrate, corrosion of metallic orthodontic appliances has been clearly seen following treatment, as evidenced by the release of nickel from these appliances in several in vitro studies [4].

The three most often utilized alloys for making brackets or arch wires are stainless steel (SS), nickel-titanium (NiTi) and copper nickel-titanium (CuNiTi) wires. Stainless steel is often used in orthodontics for making brackets, arch wires, bands, and ligatures among other equipment. Metals like chromium, nickel, and others give stainless steel its resistance to corrosion. It is an iron and carbon alloy [5]. The market offers a wide range of stainless-steel alloys, some of which are useful in orthodontics because of their properties [6]. The orthodontic wires industry has undergone a revolution thanks to the introduction of nickel-titanium (NiTi) alloys, making the ideal of applying continuous and consistent stresses virtually a reality. To take advantage of the exceptional super-elasticity and shape memory capabilities of NiTi alloys, numerous advancements were made in the production of austenite active (super-elastic) and martensite active (heat activated) NiTi wires [7].

Unfortunately, even though NiTi orthodontic wires are now produced, corrosion still occurs, especially when they are exposed to corrosive environments. CuNiTi, or NiTi arch wires, first surfaced in the 1990s and are mostly made of nickel, titanium, copper, and chromium [8]. In order to offer more defined transition temperatures, copper (an efficient heat conductor) was added to nickel and titanium [9]. This ensured the formation of more homogeneous loadings from arch to arch and from end to end, enhancing the effectiveness of tooth movement. The CuNiTi arch wires would have a lower elasticity module compared to the typical heat-activated and super-elastic NiTi arch wires, meaning they would undergo comparable deformations before activation loadings that were lower, demonstrating a greater capacity to withstand stresses [10].

According to studies, among orthodontic alloys, the nickel (Ni) ion is the one that causes allergies to flare up the most, followed closely by chromium (Cr). Additionally, it has been demonstrated that the most prevalent dental alloy metals (Ni, Cr, Co, Fe, Ti) may have toxic or biological effects that are either systemic or local [11]. In example, various pathologic oral tissue reactions, such as contact stomatitis, multiform erythema, and gingival hypertrophy, have been documented during orthodontic treatment. These reactions may be associated with the toxic effects of metal ions emitted from fixed orthodontic appliances [12].

2. Experimental

2.1 Materials

Dental alignment arch wires of stainless steel (SS), nickel titanium (NiTi) and copper doped nickel titanium (CuNiTi) were purchased from local dental material store. Artificial saliva obtained from nanochemazone. NaCl purchased from Merck. For electrochemical studies we are taken the working electrode as arch wire of both saliva treated and non-treated, reference electrode as Ag/AgCl, and counter electrode as platinum mesh (1×1 cm^2) and 10 ml of 0.5 M NaCl as electrolyte.

2.2 Analysis of nickel ions released from stainless steel, NiTi and CuNiTi arch wires

The arch wire was used as working electrode. We took a set of arch wires of SS, NiTi and Cu-NiTi and cut them at a length of 5.5 cm of each arch wire and only 1 cm of each wire was exposed and the rest of the wire was masked [13]. Then, a set of arch wires (1 cm length) (SS, NiTi and Cu-NiTi) were immersed in artificial saliva (pH-8) for 3 days and electrochemically analyzed after three days. The amount of Ni ions released from the sample were evaluated using electrochemical techniques of cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (Tafel) method.

3. Results

3.1 Electrochemical analysis of set of arch wire and the effect of saliva

3.1.1 Cyclic voltammetry (CV)

The CV was performed with saliva treated SS (s-SS), NiTi (s-NiTi) and CuNiTi (s-CuNiTi) arch wires as well as non-saliva treated SS (n-SS), NiTi (n-NiTi) and CuNiTi (n-CuNiTi) arch wires in 0.5 M NaCl at 50 mV s^{-1} to analyze the stability and compare it. Initially, the saliva treated and non-saliva treated 1 cm length of working electrode of arch wire was immersed in the electrolyte and run the CV with the potential window of 0 V to 0.6 V (Fig. 1). The results of the s-SS and s-NiTi showed higher capacitive current than the n-SS and n-NiTi, respectively. But the capacitive current difference between s-CuNiTi and n-CuNiTi was very low or not comparable (more or less similar). It showed the high corrosion resistance property of the n-SS, n-NiTi and CuNiTi (after saliva treatment CuNiTi was not affected by saliva or less affected compare to SS and NiTi). The n-SS arch wire showed 0.6×10^{-6}A and s-SS showed 0.8×10^{-6}A for a stabilized current sensitivity at 0.3 V (Fig. 1a). There was a current difference between n-SS and s-SS, which was 0.2 μA, this indicated the effect of saliva on the SS arch wire, which affected the corrosion resistance properties of the SS arch wire and also the n-SS corrosion resistance property was higher. The n-NiTi showed 0.3×10^{-6}A and s-NiTi showed 0.6×10^{-6}A for a stabilized current sensitivity at 0.3 V (Fig. 1b). The current difference between n-NiTi and s-NiTi was 0.3 μA, this indicated the effect of saliva on the NiTi arch wire, which was affected the corrosion resistance properties of the NiTi arch wire and also the n-NiTi corrosion resistance property was higher. The n-CuNiTi showed 0.5×10^{-6}A and s-CuNiTi showed 0.45×10^{-6}A for a stabilized current sensitivity at 0.3 V (Fig. 1c). The current difference between n-CuNiTi and s-CuNiTi was 0.05 μA, this had indicated the effect of saliva on the CuNiTi arch wire was very less and also the corrosion resistance properties of the CuNiTi arch wire was very high.

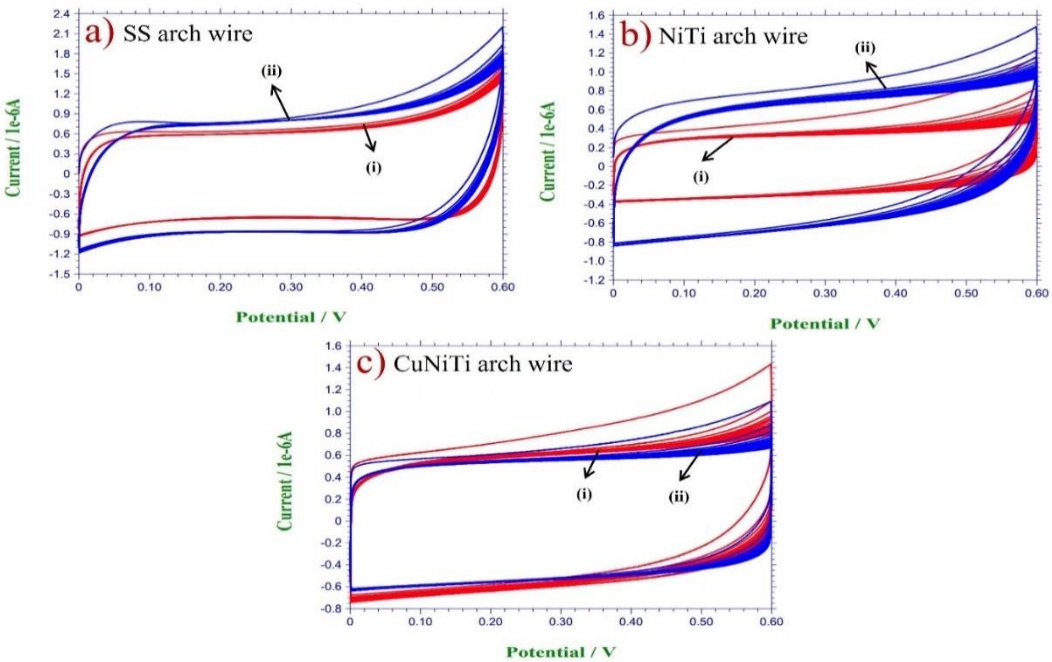

Figure 1: Cyclic voltammograms (CVs) of comparison plot for the stability study of (i) saliva non-treated and (ii) saliva treated arch wires of (a) SS, (b) NiTi, (c) CuNiTi in 0.5 M NaCl at 100 mV s^{-1} scan rate.

3.1.2 Open circuit potential (OCP) analysis

We performed OCP with both control and saliva treated arch wires of SS, NiTi and CuNiTi in 0.5 M NaCl with set time of 900 s and analyzed the voltage stability of the material with respect to time. The OCP data was shown in Fig. 2, the OCP represents the corrosion tendency of a material; a more positive OCP indicates a surface with lower electrochemical activity. The results show that the OCP value increased slowly at the beginning of the immersion but tended to become stable after 800 sec due to the equilibrium of the passive film formation. Figs. 2a, 2b and 2c, indicated that both control and saliva treated arch wires had a different origin of potential. In SS arch wire, the s-SS was stabilized at low voltage than n-SS which maintained up to 900 sec and the OCP of s-SS more stable compared with n-SS (Fig. 2a), whereas the n-SS was even tending to increase in its voltage from the origin and stabilized further 900 sec. It concluded that the s-SS was electrochemically more stable than n-SS (because the effect of saliva). Hence the stabilized OCP values at 900 sec for n-SS and s-SS were 0.105 V and 0.065 V, respectively. In this case, the s-SS was more stable because the SS was contact with saliva and lost their corrosion resistance properties as well as made it electrochemically stable, which led to n-SS to high corrosion resistance.

Moreover, in NiTi and CuNiTi arch wires also shown an origin of potential difference between both control and saliva treated arch wires (Figs. 2b and 2c). But here the s-NiTi and s-CuNiTi arch wires were stabilized at high voltage than n-NiTi and n-CuNiTi arch wires, also it maintains up to 900 s. This indicated that the s-NiTi and s-CuNiTi were electrochemically less stable compared to n-NiTi and s-NiTi. Hence the stabilized OCP value was 900 s of n-NiTi and n-CuNiTi were -0.072 V and -0.105 V, as well as for s-NiTi and s-CuNiTi were -0.016 V and -0.066 V, respectively. It means the electrocatalytic activities of the s-NiTi and s-CuNiTi were weaker than n-NiTi and n-CuNiTi, respectively. It indicated that s-NiTi and s-CuNiTi were reacted to the saliva and the corrosion resistance properties was reduced.

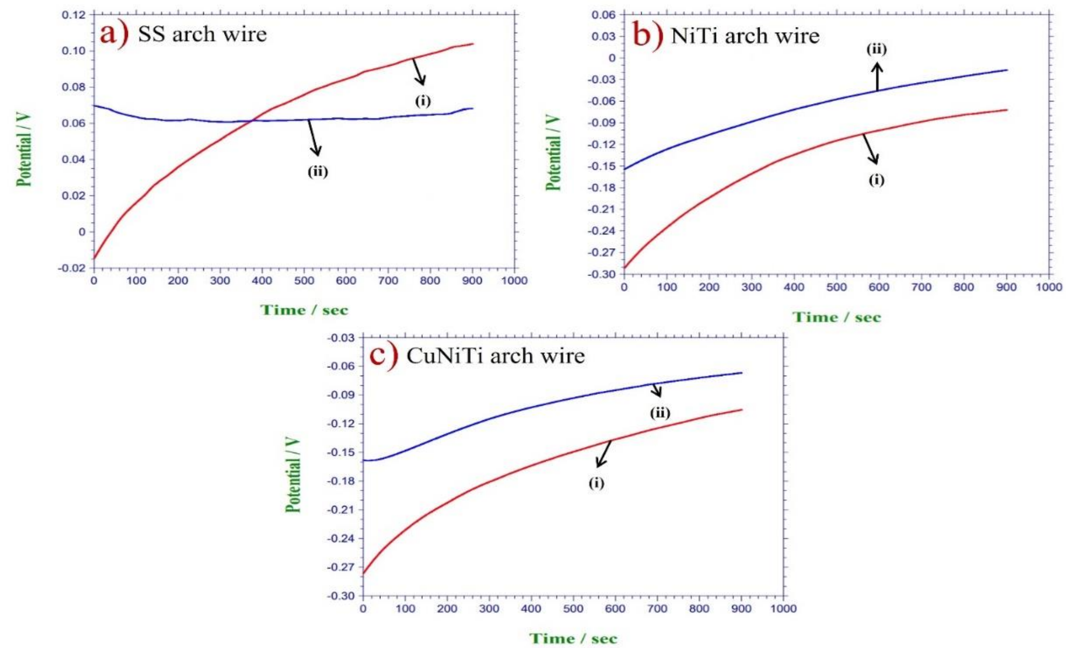

Figure 2. OCP curves of (i) saliva non-treated and (ii) saliva treated arch wire of (a) SS, (b) NiTi, (c) CuNiTi in 0.5 M NaCl with set time of 900 s.

3.1.3 Electrochemical impedance spectroscopy (EIS) analysis

The EIS experiments were conducted in 0.5 M NaCl using both saliva treated and saliva untreated arch wires of SS, NiTi and CuNiTi (Fig. 3). It confirmed and compared the corrosion resistance property between saliva treated and saliva untreated arch wires. The corrosion resistance property of s-SS, s-NiTi and s-CuNiTi was reduced compare to n-SS, n-NiTi and n-CuNiTi because of the effect of saliva. Fig. 3a shows the EIS data of n-SS and s-SS arch wires, there was no any semicircle found on this EIS data of Nyquist plot and clearly showed the electrolytic resistance was 11 ohms, which represented that the n-SS and s-SS was a good conductor and there was no any resistance or very low amount of resistance. But this figure showed the peak difference between them, which indicated that the s-SS had more corrosion resistance compare to n-SS (because the s-SS reacted with saliva and some oxide layer was formed on its surface).

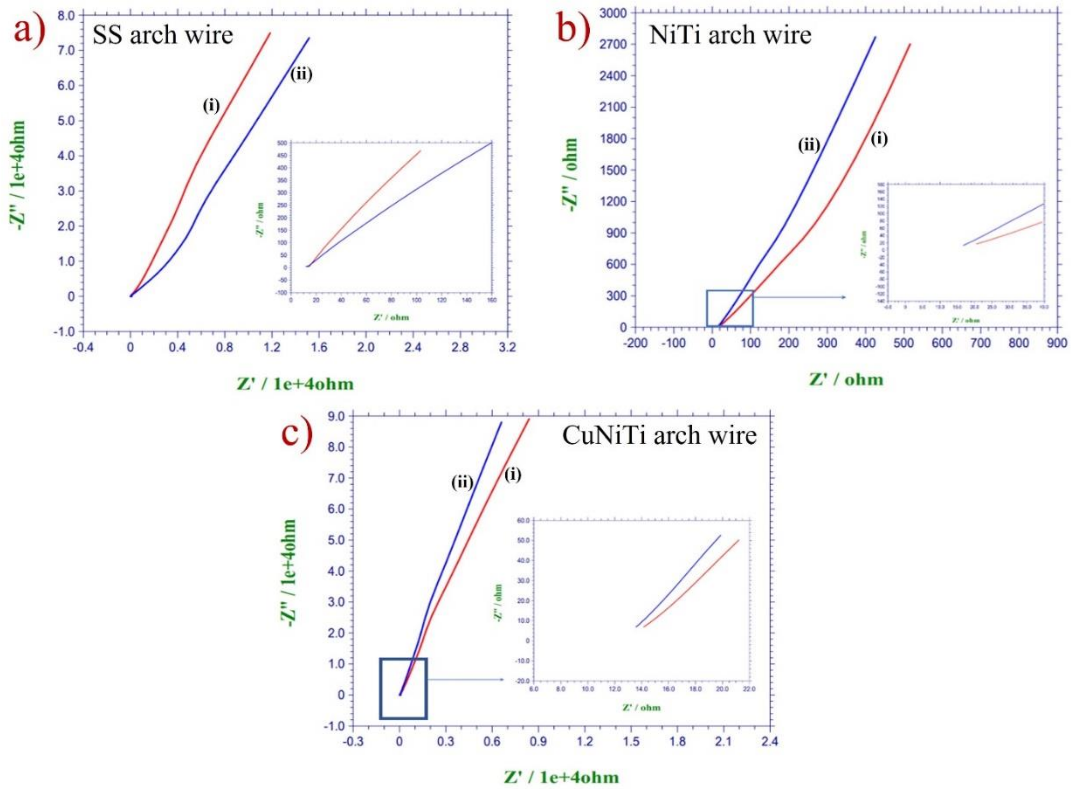

Figure 3. EIS data of (i) saliva non-treated and (ii) saliva treated arch wires: (a) SS, (b) NiTi, (c) CuNiTi in 0.5 M NaCl.

Figs. 3b and 3c show the EIS data of saliva treated and saliva untreated arch wires of NiTi and CuNiTi, respectively. There was no semicircle in the obtained Nyquist plot of NiTi and CuNiTi arch wires. Although, here the EIS curve showed that the s-NiTi and s-CuNiTi had lower impedance (Z') than n-NiTi and n-CuNiTi, respectively. Because the s-NiTi and s-CuNiTi arch wires surface was reacted with the saliva and undergone some oxide layer formation to lose their corrosion resistance properties and increased the conductivity of the arch wire. Compare to NiTi arch wire, the CuNiTi arch wire showed less difference in impedance curve. The solution resistance of the NiTi and CuNiTi were 15.5 and 14.5 ohms, respectively.

3.1.4 Potentiodynamic polarization (Tafel) analysis

Finally, the Tafel technique was carried out under a potential range from −1.0 V to + 0.4 V in 0.5 M NaCl using both control and saliva treated SS, NiTi and CuNiTi arch wires, and calculated various parameters of results, such as corrosion potential (V), linear polarization (R), corrosion current (A) and current rate (g/h). Figure 4 displays the potentiodynamic polarization results, which showed an obvious passivation region for both control and saliva treated (SS, NiTi and CuNiTi) arch wire curves, indicated that the saliva can etch the corrosive property of the material day by day. Hence the corrosion potentials for n-SS and s-SS were −0.244 V and −0.289 V, for n-NiTi and s-NiTi were −0.566 V and −0.564 V, for n-CuNiTi and s-CuNiTi were, −0.453 V and −0.483 V, respectively. By using the area of the wire, formula weight, number of electrons, and density in the corrosion rate calculation, the linear polarization and corrosion current were found using the CHI760E software (Table 1). Figure 4a shows the Tafel plot of n-SS and s-SS, the linear polarization (R) of s-SS (103352) was lesser than the n-SS (195278) as well as the corrosion current of s-SS (4.787×10^{-7}A) was higher than the n-SS (2.246×10^{-7}A). Therefore, the corrosion current indicates the overall corrosion rate of the material. Hence, the corrosion rate of the n-SS and s-SS were 2.340×10^{-7} and 4.987×10^{-7} g/h, respectively (Table 1). Compare to n-SS, the s-SS corrosion rate was high because of the material reacted with saliva to reduce their corrosion resistive property.

Moreover, Figure 4b shows the Tafel plot of n-NiTi and s-NiTi, the R of s-NiTi (391467) was lesser than the n-NiTi (436486) and the corrosion current of s-NiTi (1.133×10^{-7}A,) was higher than the n-NiTi (1.036×10^{-7} A). The corrosion rates of the n-NiTi and s-NiTi were 1.063×10^{-7} and 1.163×10^{-7} g/h, respectively. The corrosion rates of n-NiTi and s-NiTi were not shown that much difference, which concluded that the corrosion rate of s-NiTi was less than s-SS. Furthermore, the CuNiTi used to record the polarization, the n-CuNiTi and s-CuNiTi Tafel plot were shown in Figure 4c. The 'R' of s-CuNiTi (494848 ohms) was lesser than the n-CuNiTi (602670 ohms) and the corrosion current of s-CuNiTi (8.855×10^{-8} A) was higher than the n-NiTi (7.159×10^{-8} A). The corrosion rates of the n-NiTi and s-NiTi were 7.346×10^{-8} and 9.086×10^{-8} g/h, respectively. The s-CuNiTi wire showed greater corrosion resistance compared to s-SS and s-NiTi after the interaction with saliva.

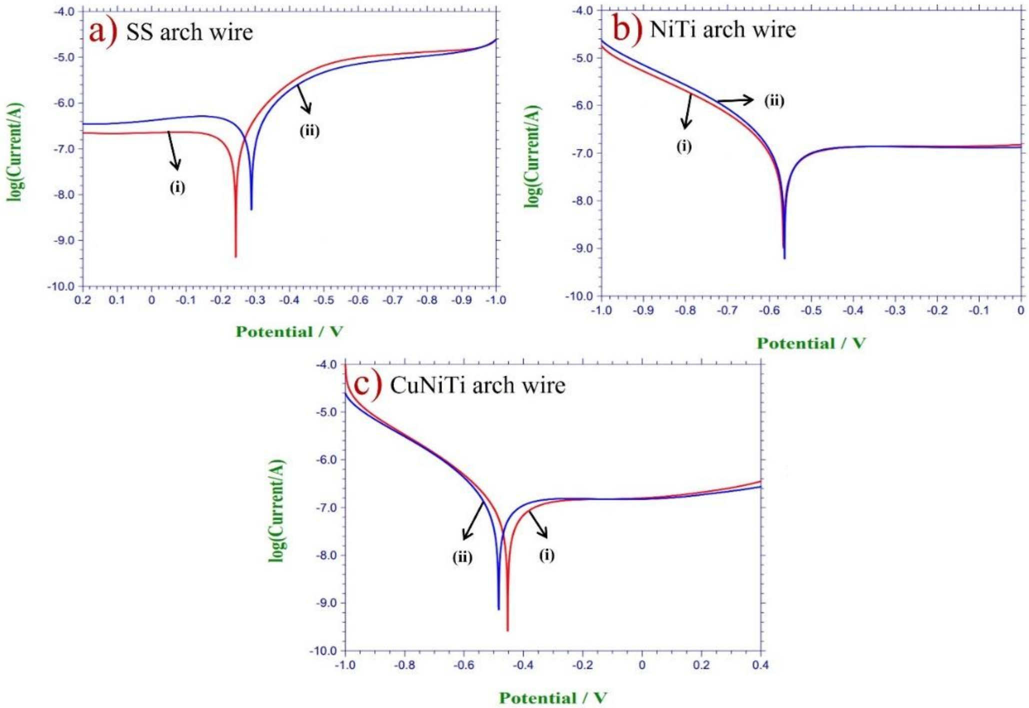

Figure 4. Polarization (Tafel) plot of (i) saliva non-treated and (ii) saliva treated arch wires of (a) SS, (b) NiTi, (c) CuNiTi in 0.5 M NaCl with potential window of −1.0 V to +0.4 V.

Table 1. Fitted results of corrosion potential, linear potential, corrosion current and corrosion rate

Sample	Corrosion potential (V)	Linear polarization (Ω)	Corrosion current (A)	Corrosion rate (g/h)
n-SS	−0.244	195278	2.246×10^{-7}	2.340×10^{-7}
s-SS	−0.289	103352	4.787×10^{-7}	4.987×10^{-7}
n-NiTi	−0.566	436486	1.036×10^{-7}	1.063×10^{-7}
s-NiTi	−0.564	391467	1.133×10^{-7}	1.163×10^{-7}
n-CuNiTi	−0.453	602670	7.159×10^{-8}	7.346×10^{-8}
s-CuNiTi	−0.483	494848	8.855×10^{-8}	9.086×10^{-8}

4. Discussions

The corrosion resistance of NiTi orthodontic wire products will vary between every manufacturer. In the present study, the nickel released from three different orthodontic wires in the synthetic saliva was analyzed after 3rd day of immersion. The corrosive effects of various environmental factors on the alloys used in dental prosthetics have been extensively studied by several writers. It was essential that the alloys used in the prosthesis, need to be protected against chemical corrosion. According to descriptions, these alloys typically also release metals into the saliva. The environment of the salivary glands and metal leaching were strongly correlated with pH [14]. Due to its basic nature and ease of alloy formation when mixed with other metals, nickel is a metal that was frequently utilized in orthodontic treatments. Arch wires (made of stainless steel and nickel-titanium [NiTi]), brackets, bands, face bows, stainless steel ligatures, and stainless-steel components of removable appliances are all potential sources of nickel [15].

While 18/8 stainless steel (SS) contains 8% nickel, NiTi arch wires contain 47–50% nickel, making them the richest source of nickel in the intraoral environment of an orthodontic patient [16]. Grimsdottir et al. studied the chemical makeup of brackets, face bows, arch wires, and bands, came to the conclusion that 8–12% nickel was present in most components [17]. The CV graph shows the stability comparison of both control SS (n-SS) and saliva treated SS (s-SS), where the stability ran for 50 segments in 100 mV/s, in which there was a change in the current sensitivity between n-SS and s-SS. For a potential window of 0 V to 0.6 V, n-SS showed 1.5×10^{-6} A and s-SS showed 1.9×10^{-8} A. We evaluated the OCP of each wire in a 0.5 M NaCl electrolyte for a period of 900 s and charted the OCP's evolution. OCP measures a material's property to corrode; a higher OCP suggests a surface with less electrochemical activity. In the previous study, Ni was released from Group I (NiTi wire) at a rate of 0.93-0.04 g per day, followed by Group II (Stainless steel wire) at 0.66- 0.02 g and Group III (ion implanted NiTi wire) at 0.67- 0.02 g. The outcome showed that ion implanted NiTi and stainless-steel arch wires emitted less Ni. Compare with NiTi that was not coated (0.67- 0.02 g/day) [18]. In this study, according to the findings, the OCP value gradually increased at the start of the immersion but tended to stabilize after 800 seconds as a result of the equilibrium of passive film production and its dilution for n-SS. A measurement of potentiodynamic polarization was made. It shows the potentiodynamic polarization data of both the n-SS and the s-SS curves, clearly reveal a passivation zone, demonstrating that the saliva may gradually etch the material's corrosive property. As a result, the corrosion potentials for n-SS and s-SS were -0.244 and -0.289 V, respectively. The linear polarization and corrosion current were determined using the CHI760E software by using the area of the wire, formula weight, quantity of electrons, and density in the corrosion rate calculation. When compared the linear polarization (R) of the s-SS with the n-SS, the s-SS (103352 ohms) was a lower R value than the n-SS (195278 ohms), and the s-SS (4.787×10^{-7} A) was showed a larger corrosion current value than the n-SS (2.246×10^{-7}A). The corrosion current thus provides information about the material's overall rate of corrosion. As a result, the corrosion rates of the n-SS and s-SS were 2.340×10^{-7} and 4.987×10^{-7} g/h, respectively. A working electrode (n-NiTi and s-NiTi), a reference electrode (Ag/AgCl), a counter electrode (platinum wire), and 10 mL of 0.5 M NaCl was used as the electrolyte. The working electrodes length was 5.5 cm and 1cm of the wire was exposed into NaCl for corrosion studies. In the previous study, the maximum number of nickel ions were released in solution immersions for all types of wires, according to the results of immersion testing. The overall length of nickel ion orthodontic wire can be calculated to be roughly 15 cm if a full-mouth device is taken into consideration (including upper and lower arch) [19].

The CV graph displays the stability comparison of both n-NiTi and s-NiTi as well as n-CuNiTi and s-CuNiTi in 0.5 M NaCl with potential window of 0 V to 0.6 V, where the stability lasted for 50 segments at 100 mV/s; there was a difference in the current sensitivity between n-NiTi and s-NiTi as well as between n-CuNiTi and s-CuNiTi. In the previous study, growing interest in the composition of alloys and the release of metals during treatment has been sparked by an increase in allergic reactions to nickel and the accessibility of orthodontic treatment. Several authors have reported in vitro corrosion of orthodontic appliances, but comparisons between the studies are challenging due to differences in study designs and electrochemical factors [20]. As a result, orthodontic therapy for patients who are Ni sensitive may be difficult. To determine how much of the corrosive products are actually absorbed by the patients and the deadly consequences of released Ni in vitro cell cultures, additional research is necessary.

5. Conclusions

The release of nickel in the current study was far lower than the usual dietary consumption of nickel, which precluded any hazardous effects. It has been noted that the amount of Ni in saliva varies, and some Ni was also released from the wire. After three days, an estimated Ni release in saliva was seen. Even if it is less than the average intake of Ni and is not dangerous, the NiTi wire has discharged more Ni than SS and CuTiNi arch wires.

6. Reference

1. Huang, H.-H.; Chiu, Y.-H.; Lee, T.-H.; Wu, S.-C.; Yang, H.-W.; Su, K.-H.; Hsu, C.-C. Ion Release from NiTi Orthodontic Wires in Artificial Saliva with Various Acidities. *Biomaterials* 2003, *24*, 3585–3592, doi:10.1016/S0142-9612(03)00188-1.
2. Bass, J.K.; Fine, H.; Cisneros, G.J. Nickel Hypersensitivity in the Orthodontic Patient. *Am. J. Orthod. Dentofac. Orthop.* 1993, *103*, 280–285, doi:10.1016/0889-5406(93)70009-D.
3. Lee, T.-H.; Huang, T.-K.; Lin, S.-Y.; Chen, L.-K.; Chou, M.-Y.; Huang, H.-H. Corrosion Resistance of Different Nickel-Titanium Archwires in Acidic Fluoride-Containing Artificial Saliva. *Angle Orthod.* 2010, *80*, 547–553, doi:10.2319/042909-235.1.
4. KATIC, V.; CURKOVIC, L.; BOSNJAK, M.U.; PEROS, K.; MANDIC, D.; SPALJ, S. Effect of PH, Fluoride and Hydrofluoric Acid Concentration on Ion Release from NiTi Wires with Various Coatings. *Dent. Mater. J.* 2017, *36*, 149–156, doi:10.4012/dmj.2016-169.
5. Quadras, D.D.; Nayak, U.S.K.; Kumari, N.S.; Priyadarshini, H.R.; Gowda, S.; Fernandes, B. In Vivo Study on the Release of Nickel, Chromium, and Zinc in Saliva and Serum from Patients Treated with Fixed Orthodontic Appliances. *Dent. Res. J. (Isfahan).* 2019, *16*, 209–215.
6. Arango Santander, S.; Luna Ossa, C.M. Acero Inoxidable: Hechos Significativos Para El Ortodoncista Practicante. *Rev. Nac. Odontol.* 2015, *11*, doi:10.16925/od.v11i20.751.

7. Gravina, M.A.; Brunharo, I.H.V.P.; Canavarro, C.; Elias, C.N.; Quintão, C.C.A. Mechanical Properties of NiTi and CuNiTi Shape-Memory Wires Used in Orthodontic Treatment. Part 1: Stress-Strain Tests. *Dental Press J. Orthod.* 2013, *18*, doi:10.1590/S2176-94512013000400007.
8. Park, H.Y.; Shearer, T.R. In Vitro Release of Nickel and Chromium from Simulated Orthodontic Appliances. *Am. J. Orthod.* 1983, *84*, 156–159, doi:10.1016/0002-9416(83)90180-X.
9. Gravina, M.A.; Canavarro, C.; Elias, C.N.; Chaves, M. das G.A.M.; Brunharo, I.H.V.P.; Quintão, C.C.A. Mechanical Properties of NiTi and CuNiTi Wires Used in Orthodontic Treatment. Part 2: Microscopic Surface Appraisal and Metallurgical Characteristics. *Dental Press J. Orthod.* 2014, *19*, 69–76, doi:10.1590/2176-9451.19.1.069-076.oar.
10. Garcia, F.G.; Barbosa, J.A.; Basting, R.T. Comparative Analysis of Plastic Deformation of NiTi and CuNiTi Wires Submitted to Mechanical Cycling. *Brazilian Dent. Sci.* 2017, *20*, 78–86, doi:10.14295/bds.2017.v20i3.1438.
11. Hussain, H.D.; Ajith, S.D.; Goel, P. Nickel Release from Stainless Steel and Nickel Titanium Archwires – An in Vitro Study. *J. Oral Biol. Craniofacial Res.* 2016, *6*, 213–218, doi:10.1016/j.jobcr.2016.06.001.
12. Sheibaninia, A. Effect of Thermocycling on Nickel Release from Orthodontic Arch Wires: An In Vitro Study. *Biol. Trace Elem. Res.* 2014, *162*, 353–359, doi:10.1007/s12011-014-0136-z.
13. Haddad, A.C.S.S.; Tortamano, A.; Souza, A.L. de; Oliveira, P.V. de An in Vitro Comparison of Nickel and Chromium Release from Brackets. *Braz. Oral Res.* 2009, *23*, 399–406, doi:10.1590/S1806-83242009000400009.
14. Jithesh, C.; Venkataramana, V.; Penumatsa, N.; Reddy, S.N.; Poornima, K.Y.; Rajasigamani, K. Comparative Evaluation of Nickel Discharge from Brackets in Artificial Saliva at Different Time Intervals. *J. Pharm. Bioallied Sci.* 2015, *7*, S587-93, doi:10.4103/0975-7406.163557.
15. Rongo, R.; Ametrano, G.; Gloria, A.; Spagnuolo, G.; Galeotti, A.; Paduano, S.; Valletta, R.; D’Antò, V. Effects of Intraoral Aging on Surface Properties of Coated Nickel-Titanium Archwires. *Angle Orthod.* 2013, *84*, 665–672, doi:10.2319/081213-593.1.
16. Mikulewicz, M.; Chojnacka, K. Release of Metal Ions from Orthodontic Appliances by In Vitro Studies: A Systematic Literature Review. *Biol. Trace Elem. Res.* 2011, *139*, 241–256, doi:10.1007/s12011-010-8670-9.
17. Grimsdottir, M.R.; Gjerdet, N.R.; Hensten-Pettersen, A. Composition and in Vitro Corrosion of Orthodontic Appliances. *Am. J. Orthod. Dentofac. Orthop.* 1992, *101*, 525–532, doi:10.1016/0889-5406(92)70127-V.
18. Senkutvan, R.S.; Jacob, S.; Charles, A.; Vadgaonkar, V.; Jatol-Tekade, S.; Gangurde, P. Evaluation of Nickel Ion Release from Various Orthodontic Arch Wires: An in Vitro Study. *J. Int. Soc. Prev. Community Dent.* 2014, *4*, 12–16, doi:10.4103/2231-0762.130921.
19. Kovac, V.; Poljsak, B.; Bergant, M.; Scancar, J.; Mezeg, U.; Primozic, J. Differences in Metal Ions Released from Orthodontic Appliances in an In Vitro and In Vivo Setting. *Coatings* 2022, *12*, 190, doi:10.3390/coatings12020190.
20. Mirhashemi, A.; Jahangiri, S.; Kharrazifard, M. Release of Nickel and Chromium Ions from Orthodontic Wires Following the Use of Teeth Whitening Mouthwashes. *Prog. Orthod.* 2018, *19*, 4, doi:10.1186/s40510-018-0203-7.