Evaluation of Corrosion Mechanisms in Stainless Steel Orthodontic Retainer Wires

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EVALUATION OF CORROSION MECHANISMS IN STAINLESS STEEL ORTHODONTIC RETAINER WIRES

by

Jamie E. Martin, DDS

A Thesis submitted to the Faculty of the Graduate School, Marquette University, in Partial Fulfillment of the Requirement for the Degree of Master of Science

Milwaukee, Wisconsin

August 2019
ABSTRACT

EVALUATION OF CORROSION MECHANISMS IN STAINLESS STEEL ORTHODONTIC RETAINER WIRES

Jamie E. Martin, DDS
Marquette University, 2019

Objective: Orthodontic retainers fabricated from stainless steel wire and acrylic are prone to several types of corrosion in the oral environment, including stress, crevice, and galvanic corrosion. The aim of this study was to determine the relative effect of stress corrosion, galvanic corrosion, and crevice corrosion on stainless steel retainer wires.

Methods:
Three different brands of 0.032-inch stainless steel wires were tested. Six new segments (2-inch length) of each brand of wire were tested in each of four tests: 1) in an artificial saliva solution to determine a general corrosion ranking; 2) in an artificial saliva solution after a 90-degree bend was placed on the wire to examine stress corrosion; 3) in 6% iron chloride solution to simulate crevice conditions and evaluate crevice corrosion; and 4) in an artificial saliva with the wire coupled to a solder material to measure galvanic corrosion. Corrosion properties were evaluated with a potentiostat. Open circuit potential (mV) and corrosion current density (nA/mm²) were compared in tests 1-3, as well as charge (mC) in the galvanic test. Statistical comparisons were completed with analysis of variance (ANOVA) tests and T-tests.

Results:
One brand of retainer wire was not superior to the others in all tests. There was no significant difference (p>0.05) in open circuit potential (OCP) or corrosion current density between the bent and straight wires when tested in artificial saliva solution. All wires showed significantly (p<0.05) lower OCP and greater corrosion rates when placed in the iron chloride solution compared to artificial saliva. All wires were susceptible to pitting in the crevice conditions whereas pitting was observed less in the artificial saliva. The solder was anodic to the wires and produced the galvanic current.

Conclusion:
Stainless steel retainer wires have the potential to corrode via several mechanisms, but crevice corrosion appears to produce the greatest effect. Orthodontists should be aware of the potential for crevice corrosion in the fabrication and routine checkups of retainers made with stainless steel wire.
ACKNOWLEDGEMENTS

Jamie E. Martin, DDS

I would like to thank Dr. Ghada Nimeri and Dr. David Berzins for their knowledgeable and expert guidance with this thesis. This research could not have been completed without their help.
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Retention is an essential part of orthodontic treatment, as it is necessary to keep teeth in alignment after active tooth movement. The well-known “father of orthodontics,” Edward Angle, believed that teeth would not move if they were in ideal intercuspation after treatment. However, it is now generally accepted that retention is necessary for excellent long-term results due to the relapse tendency of the dentition. Relapse is likely due to gingival and periodontal tissues that require time for reorganization, pressure from the soft tissues, as well as subsequent changes in growth. Therefore, retention is crucial until the patient’s growth is essentially complete (Proffit et al., 2013).

The most common removable retainer is the Hawley retainer, which was created in the 1920s. This retainer is composed of wire, namely stainless steel wire, and an acrylic plate. The acrylic is adapted to patient’s palate, a wire bow is bent to adapt to the facial of the anterior teeth, and wire clasps are added for retention. A clear vacuum-formed retainer is another option for removable retention, and it is preferred by some patients due to its clear and therefore discreet nature. However, these clear retainers do not have the longevity that Hawley retainers provide (Proffit et al., 2013). It has been shown in a systematic review article that there are no differences between Hawley and clear retainers in respect to changes in intercanine and intermolar widths after orthodontic retention. Furthermore, in regard to occlusal contacts, cost effectiveness, patient satisfaction, and survival time, there was no sufficient evidence to support clear retainers over Hawley retainers (Mai et al., 2014).
Various alloys compose the brackets, archwires, and retainer wires used throughout orthodontic treatment. Precious metals were used in orthodontics in early years, and then stainless steel was introduced in 1929. Stainless steel has been proven over the years to be superior to noble metal alloys for orthodontic appliances, and it is the primary material of orthodontic archwires and the wire of Hawley retainers (Oh et al., 2003). It is desired in the orthodontic field due to its high yield strength, high modulus of elasticity, moderate cost, excellent formability, and high corrosion resistance. Type 300 stainless steel contains 17-25% chromium and 8-25% nickel, lesser amounts of molybdenum and manganese, and trace amounts of carbon, nitrogen, silicon, phosphorus, sulfur, and selenium (Kusy et al., 2002). The typical composition for orthodontic use is 18% chromium and 8% nickel, also known as 18-8 stainless steel. Nickel and molybdenum are added for corrosion resistance, but chromium is the most important element in resisting corrosion. The reaction of chromium, a highly reactive base metal, with oxygen creates an adherent passive chromium oxide film that protects it from localized attack and makes it “stainless.” The corrosion resistance of stainless steel is due to this passive layer, which spontaneously forms and reforms (Rustandi, 2017). Therefore, corrosion resistance is critically dependent on the ability of this passive layer to be maintained (Kao, 2010).

Over time, as orthodontic appliances are immersed in the oral environment, they are constantly exposed to conditions making them susceptible to corrosion. Conditions of the oral cavity such as fluctuating temperature, pH changes by acidic foods and drink, bacterial flora and its byproducts, and enzyme activity promote corrosion. Orthodontic treatment may lead to alterations in the oral environment that further facilitate corrosion,
including an increase in plaque accumulation and increase in salivary microbial levels. Various mechanisms of corrosion may occur, such as stress corrosion, crevice corrosion, and galvanic corrosion. Stress corrosion occurs at a site of stress due to an applied load, for example when a bend is placed in the wire. The bend may increase the surface roughness of the wire, increasing the chance of a localized surface attack. As corrosion progresses, the surface is roughened and there is a higher potential for further corrosion, which ultimately leads to breakage and failure of the wire (Wang et al., 2007).

Crevice corrosion occurs at areas where oxygen cannot freely circulate leading to accumulation of chloride salts, plaque-forming microflora, and moisture from the environment. These areas become oxygen deficient, and oxygen depletion affects the ability of the passive layer to regenerate (Eliades, 2002). There is also a decrease in the pH, facilitating a corrosive environment. Potential areas for crevice corrosion are those between the exposed stainless steel wire and the acrylic embedded wire in Hawley retainers.

Galvanic corrosion occurs when two dissimilar metals in a conductive solution become electrically coupled to each other. The driving force for the galvanic corrosion cell is the difference in the electrochemical potential between the two metals (House et al., 2008). The more electronegative metal will become the anode and will corrode, and the more electropositive or nobler metal is the cathode and is more corrosion resistant than the less noble metal. Galvanic corrosion is thus of concern in orthodontics due to the many metal alloys present in the various archwires, brackets and retention appliances placed intraorally. When solder is added to create a mechanically active soldered joint, a galvanic cell is created, and there is an increased potential for corrosion (Eliades, 2002).
As corrosion occurs intraorally through these various mechanisms, it is important to consider potential side effects to the patient. Corrosion involves two reactions, reduction at the cathode and oxidation (corrosion) at the anode. The oxidation reaction may continue until the metal is completely consumed, unless the passive layer can be reformed by the metal to protect it. As corrosion continues, it results in the release metallic ions including iron, chromium and nickel into solution, which may cause adverse patient reactions. Nickel and chromium are the most notable as they may produce toxic, carcinogenic, or allergic effects to the patient (Fraunhofer, 1997).

Reduced or absent corrosion is a critical factor in the longevity of fabricated orthodontic retainers. Corrosion alters the mechanical properties by causing an increase in the surface roughness as well as a decrease in the mechanical strength of the alloy. Surface roughness leads to increased plaque and bacteria, which increases risk of caries and gingivitis, and mechanical strength causes ultimate failure of the appliance. Secondly, there may be potential systemic or local toxic effects to patients as they ingest the metal ions released during corrosion, raising the issue of biocompatibility of the material. Therefore, it is important for orthodontists to understand the possible mechanisms and severity of corrosion of orthodontic retainers. It is hypothesized that in comparison to wire in artificial saliva solution, there will be higher corrosion observed in bent wire, wire in a solution simulating crevice corrosion (iron chloride solution), and wire coupled to solder creating galvanic corrosion.
Corrosion of stainless steel and other orthodontic alloys

With the introduction of stainless steel in 1929, precious metal alloys become obsolete due to the properties stainless steel could provide. In the 1950s, type 300 stainless steels were being used in the majority of orthodontic materials and were composed of 17-25% chromium, 8-25% nickel, with a balance of iron. Chromium facilitated formation of the passive layer, and nickel stabilized the austenite structure, which further improved corrosion resistance. Stainless steel was desired due to its corrosion resistance, high strength, and high stiffness, which is 93-100% more than conventional carbon steels (Kusy, 1997). However, this corrosion resistant oxide layer is not infallible, and corrosion of steel occurs when its oxide layer is disrupted or as it slowly dissolves over time due to exposure to oxygen or its environment. The oral cavity is an acidic environment due to the constant supply of acidic foods and drinks, and it is exposed to fluoride containing products that have been shown to increase corrosion (House et al., 2008).

Studies have been conducted to compare the corrosion resistance of different alloys to that of stainless steel, including nickel-titanium (NiTi) and titanium molybdenum (TMA). A study from 2018 used potentiodynamic tests to evaluate the amount of corrosion of these three types of orthodontic archwires. All three alloys showed corrosion in an artificial saliva environment. They found that the highest corrosion resistance and lowest corrosion current density (Icorr) was in the NiTi wires,
and that lowest corrosion resistance and highest Icorr was in stainless steel (Malkiewicz et al., 2018).

Pulikkottil et al. conducted a study in 2016 that also examined these three alloys as well as ion-implanted (low-friction) titanium molybdenum (L-TMA) archwires in acidic fluoride-containing artificial saliva. The study aimed to compare three alloys similar to the study by Malkiewicz et al., and also to determine if the presence of the fluoride ion affected corrosion. It was determined that L-TMA had the best corrosion resistance, followed by TMA, then NiTi, and stainless steel had the worst corrosion resistance. Authors concluded that the chemical composition of the wire is the primary factor determining corrosion, and the surface roughness of the wire is only secondary. They found that the presence of fluoride ion caused a decrease in corrosion resistance due to the reaction of sodium fluoride with the chromium oxide passive film on the wire (Pulikkottil et al., 2016).

Fluoride ions are aggressive towards the passive layer (chromium oxide) on the surface of the wires. It is known that fluoride may contribute to pitting corrosion, as this ion penetrates the interface between the oxide layer and the metal. Barcelos et al. evaluated the open circuit potential of stainless steel and NiTi wire in artificial saliva with and without fluoride ions, and the nickel content found in solution. There was significantly higher nickel release in the presence of fluoride ion, similar to what was found in previous literature (Barcelos et al., 2013).

**Forms of corrosion**

Various forms of corrosion occur in metals, including crevice corrosion, galvanic corrosion, and stress corrosion. Crevice corrosion is specifically detrimental to Hawley
orthodontic retainers composed of stainless steel wire, a corrosion resistant alloy, and an acrylic plate. Kusy et al. conducted a study where electron spectroscopy was used to evaluate control and corroded orthodontic retainers. Rampant corrosion was observed on these retainers, specifically crevice corrosion where the stainless steel wire meets the acrylic plate of the retainer. They determined that stainless steel was susceptible to rampant corrosion when the passive layer was reduced due to the bacterial and hostile oral environment. With the depletion of chromium and nickel, the passive layer protecting the stainless steel is reduced and corrosion occurs. It was found that there were both iron and chromium oxidation products present in the corroded areas of these retainers (Kusy et al., 2002).

Stress corrosion occurs due to tensile stress placed on a wire while it is in a corrosive medium. Stress corrosion is particularly important in the field of orthodontics as wires and oral appliances remain in the patient’s oral cavity for extended periods of time during active treatment as well as in the retention phase. While information regarding the applied load on the corrosion resistance of orthodontic wire is limited, breakage of NiTi wires placed intraorally for long periods of time has been reported. Wang et al. evaluated the mechanisms of cracking of NiTi wire under constant loading stress, and found that a tool-made notch placed in the wires can cause stress corrosion cracking. It was reported that this wire was most susceptible to cracking when it was at high stress and low pH (Wang et al., 2007). Huang evaluated stressed NiTi and stainless steel wires in artificial saliva to determine the effects of an acidic environment and applied load on corrosion resistance. It was reported that corrosion protection potential is
decreased with decreasing pH, and that the stressed stainless steel wire was more susceptible to pitting corrosion than the stressed NiTi wire (Huang, 2003).

Galvanic corrosion is facilitated in the oral environment by the various metal alloys in orthodontic appliances. A study by Tahmasbi et al. in 2015 compared the ion release of stainless steel brackets coupled to nickel-titanium (NiTi) and to stainless steel wires. While both wires led to ion release, there was a greater release when the NiTi wires were coupled to the stainless steel brackets (Tahmasbi et al., 2015). This is logical due to the nature of galvanic corrosion, as it occurs when two dissimilar metals with different corrosion potentials are coupled. The presence of a soldered joint in orthodontic appliances exacerbates corrosion due to the potential for galvanic currents when immersed in the oral cavity.

Vahed et al. conducted a study in 2007 to evaluate the effects of artificial saliva on the mechanical strength of orthodontic soldered stainless steel joints. It was found that there was a significantly higher tensile failure load of the joints after exposure to saliva. This is due to the galvanic nature of the solder-stainless steel interface, leading to accelerated corrosion and weakening of the joint (Vahed et al., 2007). It is known that silver-based solder coupled to stainless steel causes galvanic current and the subsequent release of copper and zinc. These are elements that are the most commonly leached out of silver-based solder alloys. These ions have the potential to cause reactions in the patient, as described in a case study from 1995 by Bishara. In this study, a patient presented with sloughing oral mucosa level to the soldered joint of a Hawley retainer, and it was concluded that the retainer caused this allergic inflammatory reaction (Bishara, 1995).
Clinical relevance of corrosion resistance

Various factors including type of alloy and environment that the wire is immersed in may determine the corrosion resistance of the wire, and various types of corrosion may occur. However, it is clear that corrosion of orthodontic wires can and will occur in the intraoral environment. Corrosion is of concern to the orthodontist for two main reasons. First, there are potential local or systematic effects produced by corrosion byproducts. Secondly, clinicians should be aware of the effects that corrosion has on the clinical performance and physical properties of the appliance.

It has been shown that in an acidic environment, corrosion takes place and the surface of different alloys deteriorates. While this study focuses on orthodontic retainers, the ability for archwires and brackets to facilitate sliding mechanics and have low friction may be affected, as well as the mechanical properties of the wire. Friction affects the clinical performance of the orthodontic wire, and corrosion increases the frictional force due to an increase in surface roughness (Chaturvedi, 2010). There is little research regarding the surface characteristics of orthodontic wires and brackets after intraoral corrosion.

Concern has been expressed as to the biotoxicity of corrosion products released during the intraoral corrosion process, and controversial results have been reported. The major products of corrosion have potential adverse affects and include iron, chromium, and nickel. Nickel and chromium have raised the most concern due to their reported potential for allergic or carcinogenic effects. An article from 2002 states “nickel complexes in the form of arsenides and sulfides are known carcinogens, allergens, and mutagens” (Eliades, 2002). Nickel has been shown to be carcinogenic in pure form as
well as in compounds, and it inhibits chemotaxis of leukocytes, as well as promotes an inflammatory response in soft tissues. However, it is controversial whether or not the release of corrosion products is an allergic and/or carcinogenic risk to orthodontic patients (Eliades, 2002).

Side effects of intraoral corrosion, in particular that of hypersensitivity, were discussed in a review article by Castro et al. in 2015. Nickel is the most common metal to induce allergic reactions and is a component of many orthodontic alloys. Although stainless steel has a nickel content of 8%, the ions are bound in a crystal lattice making them unable to react. However, when the protective passive layer is disrupted, these metal ions can be released into the oral cavity. Furthermore, it was stated that although there is a release of ions, the amount released is far lower than that from a daily diet, and that its impact on the patient’s health is not fully understood (Castro et al. 2015). It has also been stated that nickel release is only 10% and chromium is 0.25% of the amount ingested from one’s diet, making the amount insignificant (Fraunhofer, 1997). An interesting point was raised in an article from 2008, which stated that while nickel can be detected in saliva, it is not actually absorbed in the bloodstream (House et al., 2008). A cross-sectional study evaluated the saliva and blood samples of orthodontic patients and found that while there was an increase in the amount of nickel in saliva during the study, there was no increase in the serum level (Kerosuo et al., 1995).

Genotoxic effects of the products of corrosion have been studied, and contradictory results have been found. An in vivo study by Faccioni et al. in 2003 found that metal release from fixed orthodontic appliances may damage DNA in oral mucosa cells (Faccioni et al., 2003). However, conflicting results were reported in an in vitro
study by Angelieri et al. in 2011, where corrosion eluates from orthodontic brackets were evaluated to determine if they induced genetic damage. Genotoxicity tests were conducted to indicate carcinogenicity of the compound and evaluate if the compounds caused DNA damage, gene mutation, and transformation of cells. It was concluded that the corrosion eluates did not induce DNA damage, thus were not genotoxic (Angelieri et al., 2011). Similar results were reported by Alves et al. in 2016, where corrosion eluates of mini-implants immersed in artificial saliva were evaluated, and it was found that no changes in cell viability or morphology were produced (Alves et al., 2016).

However, other studies have reported an adverse effect to the release of these ions from corrosion of orthodontic appliances. An article published in 1997 states “…some quite serious conditions such as lichen planus, leukoplakia, and oral cancer have been ascribed to galvanic cells in the mouth” (Fraunhofer, 1997). This article emphasizes that the effect is caused by the difference in potential within the galvanic cell, rather than the release of metal ions/corrosion products. They claim that the incidence of adverse reactions in patients undergoing orthodontics is 1:100, and effects of corrosion include allergic and tissue reactions and metal ion release (Fraunhofer, 1997). In spite of the low level release of ions from orthodontic appliances (‘a safety threshold’), there have been reports of hypersensitivity to orthodontic appliances. Removal of these appliances showed a clear improvement in the various symptoms that were reported (Kolokitha, 2009; Ehrnrooth, 2009; Noble et al., 2008; Feilzer et al., 2008).

While controversial opinions exist about the potential toxicity of corrosion products to patients, it is clear that more investigation is needed. There are a large number of in vitro studies, and only a small number of in vivo studies. Due to the
diversity of patient exposure to these materials, composition of materials involved, and intraoral conditions, it is necessary to evaluate the safety concerns on a case-by-case basis (Martin-Camean et al., 2015). Further clinical research with larger populations is necessary to determine the biotoxicity of corrosion. However, it is clear that clinicians should be aware of the potential for as well as the various mechanisms of corrosion of intraoral orthodontic appliances.
In this study, three different commercial brands of 0.032-inch stainless steel wire were evaluated in each of 4 tests. The brands were: Dentsply GAC (Bohemia, NY), Great Lakes Orthodontics Ltd. (Tonawanda, NY), and Ortho Technology (Lutz, FL). Six segments of each brand of wire were randomly distributed into each of four tests (n=6/wire): artificial saliva as a baseline, stress corrosion, crevice corrosion, and galvanic corrosion. Each wire segment was cut to 4 inches with wire cutters. A 2-inch segment of wire was measured, and nail lacquer was used to cover the wire so that only a precise 2-inch segment of each wire was exposed. Each wire segment was tested one time.

In the first test, each brand of wire was tested in a room-temperature artificial saliva solution (Fusayama-Meyer) to determine a baseline ranking between them. Room temperature solution was used instead of the temperature of the oral environment (~35 °C). This is due to the length of each test (8 hours) and the need to keep a constant temperature for the length of every test. The artificial saliva solution was composed of 97-100% water, <0.5% urea, <0.1% each of potassium chloride, sodium chloride, sodium phosphate monobasic dihydrate, and calcium chloride dihydrate, and ≤0.0005% sodium sulfide nonahydrate. Stress corrosion was examined by placing a 90-degree bend with a 3-prong orthodontic plier in each wire. These wires were then placed in the artificial saliva solution. Crevice corrosion was examined by placing the wires in iron chloride solution, which is a solution that simulates the crevice environment. Finally, a ½” segment of Masel Ortho solder (Carlsbad, CA) was added to the artificial saliva solution.
with each segment of wire (n=6/wire) to evaluate galvanic corrosion. Each solder segment was trimmed to 2 inches with a wire cutter, and nail lacquer was added so that only ½” of wire was exposed. Each segment of solder was only used one time.

The experimental setup utilized a beaker with holes drilled in the lid to accommodate the wire (additionally the solder in the galvanic test), the reference electrode, and the counter electrode (graphite rod). Thus an electrochemical cell was created that consisted of 3 electrodes. Leads (alligator clips) were attached to the counter electrode and the wire, and tape was used to secure them in place.

A Gamry PC4 potentiostat (Warminster, PA) was used to capture polarization data and each test was conducted for 8 hours. A potentiodynamic curve was created by the system by altering potential and measuring current. The OCP (mV) or open circuit potential at 8 hours, and the Icorr (nA/mm²) or corrosion current density was recorded in the artificial saliva, stress corrosion, and crevice corrosion tests. The software extrapolated the Icorr values from the plot. In the galvanic test, charge (mC) and current at 8 hours (nA) was recorded.

Open circuit potential and corrosion current density were compared between the brands of stainless steel wire, and the saliva, stress corrosion, and crevice corrosion tests. Each brand of wire, Dentsply GAC (GAC), Great Lakes Orthodontics Ltd. (GLO), and Ortho Technology (OT), were compared as well as each mechanism of corrosion. IBM SPSS Statistics software (Armonk, NY) was used to analyze the data with ANOVA using a significance value of p<0.05, and Bonferroni (Dunn) T-tests. OCP and Icorr values were compared for artificial saliva, stress corrosion, and crevice corrosion tests. Commercial brands were compared with each other within each corrosion test.
CHAPTER 4

RESULTS

The following Tables (Tables 1-6) demonstrate the open circuit potential (OCP) and the corrosion current density (Icorr) for the baseline artificial saliva test, the stress corrosion test, and the crevice corrosion test (n=6/wire).

Table 1. OCP (mV) at 8 hours in artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (mV)</th>
<th>Test 2 (mV)</th>
<th>Test 3 (mV)</th>
<th>Test 4 (mV)</th>
<th>Test 5 (mV)</th>
<th>Test 6 (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAC</td>
<td>131.4</td>
<td>140.8</td>
<td>70.8</td>
<td>151.1</td>
<td>155.6</td>
<td>153.7</td>
</tr>
<tr>
<td>GLO</td>
<td>132.1</td>
<td>121.5</td>
<td>128.3</td>
<td>145</td>
<td>135.4</td>
<td>133.2</td>
</tr>
<tr>
<td>OT</td>
<td>121.6</td>
<td>81.75</td>
<td>120.7</td>
<td>52</td>
<td>106.9</td>
<td>114.1</td>
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</table>

Table 2. Icorr (nA/mm²) in artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (nA/mm²)</th>
<th>Test 2 (nA/mm²)</th>
<th>Test 3 (nA/mm²)</th>
<th>Test 4 (nA/mm²)</th>
<th>Test 5 (nA/mm²)</th>
<th>Test 6 (nA/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAC</td>
<td>2.0</td>
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<td>2.6</td>
<td>1.7</td>
<td>1.8</td>
<td>3.2</td>
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<tr>
<td>GLO</td>
<td>2.2</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
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<td>OT</td>
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<td>1.8</td>
<td>2.1</td>
<td>1.9</td>
<td>2.0</td>
<td>2.6</td>
</tr>
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</table>

Table 3. Stress corrosion: OCP (mV) at 8 hours for bent wire in artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (mV)</th>
<th>Test 2 (mV)</th>
<th>Test 3 (mV)</th>
<th>Test 4 (mV)</th>
<th>Test 5 (mV)</th>
<th>Test 6 (mV)</th>
</tr>
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<tbody>
<tr>
<td>GAC</td>
<td>128.9</td>
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<td>132.5</td>
<td>140.3</td>
<td>119.6</td>
<td>129.5</td>
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<tr>
<td>GLO</td>
<td>115.1</td>
<td>143.1</td>
<td>130.7</td>
<td>18.09</td>
<td>116.2</td>
<td>95.49</td>
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<tr>
<td>OT</td>
<td>77.74</td>
<td>90.56</td>
<td>92.15</td>
<td>52.4</td>
<td>83.34</td>
<td>108.9</td>
</tr>
</tbody>
</table>

Table 4. Stress corrosion: Icorr (nA/mm²) in bent wire artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (nA/mm²)</th>
<th>Test 2 (nA/mm²)</th>
<th>Test 3 (nA/mm²)</th>
<th>Test 4 (nA/mm²)</th>
<th>Test 5 (nA/mm²)</th>
<th>Test 6 (nA/mm²)</th>
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<tbody>
<tr>
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<td>2.1</td>
<td>2.6</td>
<td>2.5</td>
<td>1.8</td>
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<tr>
<td>GLO</td>
<td>2.2</td>
<td>2.1</td>
<td>2.4</td>
<td>2.8</td>
<td>3.4</td>
<td>1.5</td>
</tr>
<tr>
<td>OT</td>
<td>2.9</td>
<td>1.6</td>
<td>1.8</td>
<td>2.1</td>
<td>2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 5. Crevice corrosion: OCP (mV) at 8 hours in iron chloride solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (mV)</th>
<th>Test 2 (mV)</th>
<th>Test 3 (mV)</th>
<th>Test 4 (mV)</th>
<th>Test 5 (mV)</th>
<th>Test 6 (mV)</th>
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</thead>
<tbody>
<tr>
<td>GAC</td>
<td>-102.5</td>
<td>-111.7</td>
<td>-106.2</td>
<td>-114.7</td>
<td>-112.7</td>
<td>-107.2</td>
</tr>
<tr>
<td>GLO</td>
<td>-89.22</td>
<td>-81.16</td>
<td>-94.02</td>
<td>-93.15</td>
<td>-82.83</td>
<td>-71.69</td>
</tr>
<tr>
<td>OT</td>
<td>-86.81</td>
<td>-93.70</td>
<td>-92.74</td>
<td>-72.71</td>
<td>-98.64</td>
<td>-80.95</td>
</tr>
</tbody>
</table>
Table 6. Crevice corrosion: Icorr (nA/mm$^2$) in iron chloride solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (nA/mm$^2$)</th>
<th>Test 2 (nA/mm$^2$)</th>
<th>Test 3 (nA/mm$^2$)</th>
<th>Test 4 (nA/mm$^2$)</th>
<th>Test 5 (nA/mm$^2$)</th>
<th>Test 6 (nA/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAC</td>
<td>8900</td>
<td>11,900</td>
<td>31,400</td>
<td>5600</td>
<td>14,7900</td>
<td>12,600</td>
</tr>
<tr>
<td>GLO</td>
<td>11,500</td>
<td>6100</td>
<td>6900</td>
<td>6900</td>
<td>5800</td>
<td>4600</td>
</tr>
<tr>
<td>OT</td>
<td>13,300</td>
<td>10,300</td>
<td>7200</td>
<td>5300</td>
<td>8000</td>
<td>11,600</td>
</tr>
</tbody>
</table>

Data from the galvanic corrosion test is shown in Tables 7-8. The charge (mC) and current (I) at 8 hours (nA) are shown for each brand (n=6/wire).

Table 7. Galvanic corrosion: Charge (mC) for wire and solder in artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (mC)</th>
<th>Test 2 (mC)</th>
<th>Test 3 (mC)</th>
<th>Test 4 (mC)</th>
<th>Test 5 (mC)</th>
<th>Test 6 (mC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAC</td>
<td>3.007</td>
<td>2.552</td>
<td>3.048</td>
<td>3.476</td>
<td>4.477</td>
<td>3.706</td>
</tr>
<tr>
<td>GLO</td>
<td>2.272</td>
<td>2.323</td>
<td>3.288</td>
<td>4.082</td>
<td>2.331</td>
<td>2.206</td>
</tr>
<tr>
<td>OT</td>
<td>3.329</td>
<td>3.394</td>
<td>2.761</td>
<td>3.158</td>
<td>2.131</td>
<td>2.841</td>
</tr>
</tbody>
</table>

Table 8. Galvanic corrosion: Current (I) at 8 hours (nA) for wire and solder in artificial saliva solution

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (I)</th>
<th>Test 2 (I)</th>
<th>Test 3 (I)</th>
<th>Test 4 (I)</th>
<th>Test 5 (I)</th>
<th>Test 6 (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAC</td>
<td>24.36</td>
<td>17.34</td>
<td>18.69</td>
<td>57.62</td>
<td>90.38</td>
<td>73.04</td>
</tr>
<tr>
<td>GLO</td>
<td>71.0</td>
<td>59.21</td>
<td>75.14</td>
<td>79.87</td>
<td>64.64</td>
<td>69.56</td>
</tr>
<tr>
<td>OT</td>
<td>101.6</td>
<td>116.9</td>
<td>92.36</td>
<td>106.1</td>
<td>76.58</td>
<td>110.3</td>
</tr>
</tbody>
</table>

Lastly, Table 9 demonstrates the mean values for each brand in each test. To compare brands, means in each column with the same letter (A or B) are not significantly different. For example, when looking at one column, if one mean has an A and another has a B, their means are significantly different.

Table 9. Mean values for each brand in each corrosion test

<table>
<thead>
<tr>
<th>Artificial Saliva – Bent</th>
<th>Artificial Saliva</th>
<th>Iron Chloride</th>
<th>Galvanic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OCP (mV) @ 8 hours</td>
<td>Icorr (nA/mm$^2$) @ 8 hours</td>
<td>OCP (mV) @ 8 hours</td>
</tr>
<tr>
<td>GAC Mean</td>
<td>134 ± 32 A</td>
<td>2.1 ± 0.6 A</td>
<td>133 ± 9 A</td>
</tr>
<tr>
<td>GLO Mean</td>
<td>133 ± 8 A</td>
<td>2.6 ± 0.4 A</td>
<td>105 ± 50 A, B</td>
</tr>
<tr>
<td>OT Mean</td>
<td>100 ± 27 A</td>
<td>2.1 ± 0.3 A</td>
<td>84 ± 19 B</td>
</tr>
</tbody>
</table>
The following Figures (Figures 1-9) are potentiodynamic curves where potential is altered and current is measured. These curves demonstrate graphically the corrosion potential of the wire. Figures 1-3 represent an example of one test run of each brand in each environment as listed.

Figure 1. Potentiodynamic curves of wires in artificial saliva

Figure 2. Potentiodynamic curves of bent wires in artificial saliva
Figure 3. Potentiodynamic curves of wires in iron chloride

Figure 4. Potentiodynamic curves of GAC straight and bent wires in artificial saliva solution
Figures 7-9 demonstrate a representative run of each brand of wire in the iron chloride solution.
Figure 7. Potentiodynamic curve of GAC wire in iron chloride solution

Figure 8. Potentiodynamic curve of GLO wire in iron chloride solution
Figure 9. Potentiodynamic curve of OT wire in iron chloride solution

Figures 10-11 show the current for each brand in the galvanic test in artificial saliva as listed. Figure 10 is an early comparison of current, while Figure 11 is a comparison at 6-8 hours.

Figure 10. Early comparison of current (I) for each brand
Overall, there was no significant difference between the brands of wire, as one was not superior to the others in all tests. In the stress corrosion test, the OCP (mV) of GAC was significantly greater than OT. In the crevice corrosion test, the OCP (mV) of GAC was significantly less than GLO and OT. There was no significant difference (p>0.05) in open circuit potential (OCP) or current density between the bent and straight wires when tested in artificial saliva solution. All wires showed significantly (p<0.05) lower OCP and greater corrosion rates when placed in the iron chloride solution compared to artificial saliva. All wires were susceptible to pitting in the crevice conditions, whereas pitting was observed less in the artificial saliva. The solder was anodic to the wires and produced the galvanic current.
CHAPTER 5
DISCUSSION

Stainless steel is routinely used in the fabrication of Hawley retainers and is effective due to its corrosion resistance, strength, moderate cost, formability, and ductility. Studies have shown, however, that stainless steel is prone to corrosion in the oral environment. In this study, the relative effect of three different mechanisms of corrosion on three brands of stainless steel retainer wires was evaluated. *In vitro* laboratory conditions simulated the potential corrosive environments that oral appliances are subjected to. Data was obtained to determine if there is a difference in the corrosion rates produced by stress corrosion, galvanic corrosion, and crevice corrosion.

Most studies regarding the corrosion resistance of orthodontic wires are based on the results from cyclic polarization curves (Huang, 2003). These potentiodynamic curves are used to determine resistance to corrosion or degradation over a set period of time (Esmailzadeh, 2018). Cathodic and anodic states are demonstrated, and as the curve rises there is a change from a cathodic to anodic state, which is where corrosion occurs. A more vertical slope indicates the action of the passive layer, which protects the wire from corrosion. As the potential increases, current stays relatively the same if this passive layer is present. The Icorr and OCP (open circuit potential) were recorded for each sample in this study. The Icorr or current density is directly related to the corrosion rate. It is recorded to evaluate and compare the corrosion rate of each sample. OCP is the electrochemical potential of the metal when no current is flowing. It is a measurement of
the wire’s potential to corrode, with lower values indicating that the wire is more likely to corrode.

Prior to the beginning of this study, it was hypothesized that in comparison to wire in artificial saliva solution, there will be higher corrosion observed in bent wire, wire in a solution simulating crevice corrosion (iron chloride solution), and wire coupled to the solder creating galvanic corrosion. The data collected does not fully support this hypothesis. As seen in Table 9, the average corrosion rate for the bent wire simulating stress corrosion was not significantly different from the wire in the artificial saliva (p<0.05). The bend in the wire was placed in one motion with a 3-prong orthodontic plier. There may have been more of a change if the wire was put under additional stress by bending the wire multiple times in opposite directions. Results from this study were opposite to those recorded by Wang et al., where an increase in corrosion was observed after a notch was placed in wires (Wang, 2007). During the fabrication of a Hawley retainer, the clinician may place more than one bend in each specific location, so it is not clear whether or not results would be altered if this were the case.

Under crevice corrosion conditions, wire samples had significantly greater corrosion rate (Icorr) and OCP compared to the artificial saliva conditions (p<0.05). As seen in Table 9, values were three-fold greater for the crevice conditions. This finding is supported by the findings of Kusy et al. (2002) who examined corroded orthodontic retainers and found mottling at the crevice between the exposed stainless steel wire and the acrylic embedded wire. It was suggested that highly active, corrosive crevice environments were formed between the wire and the acrylic plate of the retainer (Kusy, 2002). Pitting was observed more frequently in the crevice conditions than any other
conditions. Pitting occurs when there is a breakdown of the passive layer and aggressive ions lead to accelerated dissolution of the wire in the form of pits. The passive film cannot reform and this rapid corrosion occurs in localized spots or pits. This characteristic is observed in the potentiodynamic curves and is more frequent in the samples in crevice conditions than the other three tests.

It is known that soldered appliances are mechanically active and are therefore more prone to corrosion (Fraunhofer, 1997). The solder was tested individually in artificial saliva and was found to possess a lower OCP and increased corrosion current rates. Therefore, when coupled with the stainless steel wires, it acted as the anode, actively corroded, and was responsible for the measured galvanic current. This finding is supported by Vahed et al., who reported a selective attack at the solder joint of the wire that reduced the tensile failure load and weakened the joint due to galvanic corrosion (Vahed, 2007).

The three commercial brands tested, GAC, GLO and OT, were seemingly identical as they were the same diameter, 0.032 inches, and all composed of stainless steel. However, different brands were used to determine if slight variations in the composition of the wires existed. While there were no significant differences in corrosion between the three brands of stainless steel wire, there was slightly greater pitting observed in the wire by Orthodontic Technology (OT) than GAC and Great Lakes Orthodontics (GLO). The OT brand also showed greater current in the galvanic tests, but this was also not significant (p>0.05).

Overall, the corrosion observed under these laboratory conditions is coincident with that found in previous studies in regard to crevice and galvanic corrosion. Stress
corrosion conditions in this study did not produce an increased susceptibility of the wire to corrosion. In regard to the potential for crevice corrosion, care should be taken in retainer fabrication as the integrity of the acrylic seal around the wire is important in reducing crevice conditions. In light of these observations, it is important for the clinician to closely monitor appliances as corrosion may lead to material degradation and rapid mechanical failure.
Stainless steel retainer wire has the potential to corrode via several mechanisms. It was observed that crevice corrosion appears to produce the greatest effect, with a significantly higher corrosion rate ($I_{corr}$) and OCP ($p<0.05$). A lesser amount of corrosion was observed but was still present in the remaining three tests: artificial saliva, bent wire in artificial saliva, and galvanic corrosion. There was not a significant difference in corrosion between commercial brands of stainless steel wire, nor was there a significant difference in corrosion between bent versus straight wires ($p>0.05$). Based on these results, orthodontists should be aware of the potential for corrosion, specifically crevice corrosion, in the fabrication and routine checkups of retainers made with stainless steel wire.
REFERENCES


