Corrosion Properties of Various Orthodontic Fixed Retention Wires

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CORROSION PROPERTIES OF VARIOUS ORTHODONTIC FIXED RETENTION WIRES

by

Tara L. Groen, DMD

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

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Objective: It is known that stainless steel and other alloys readily corrode in the oral environment. Many different wire compositions and configurations are available on the market for fixed orthodontic retainers, yet few studies have focused on the corrosion of wires used for fixed retention. The aim of this study was to determine the general and crevice corrosion properties of 7 distinct fixed retainer wires.

Methods: Seven types of fixed retainer wires were chosen for testing – solid, braided and twisted stainless steel wires; solid and twisted gold plated wires; a solid cobalt chromium wire; and a solid beta-titanium ribbon. Ten segments of each wire type were tested in both of two tests: an artificial saliva solution and a 6% iron chloride solution to determine the effects of general and crevice corrosion, respectively. Open circuit potential (OCP) at 3 hours, polarization resistance ($R_p$), and corrosion rate ($I_{corr}$) were measured with a potentiostat. Potentiodynamic curves were evaluated to determine if pitting corrosion was present. Statistical analysis was completed with analysis of variation (ANOVA) and Tukey tests.

Results: No single wire type exhibited the most or least corrosion in every category. The twisted gold plated wire had the highest corrosion rate ($I_{corr}$), significantly greater ($p<0.05$) than every other wire in both artificial saliva and iron chloride solution. The beta-titanium wire had the lowest $I_{corr}$ values in both solutions, but these values were not significantly different from other wire types. Twisted wires displayed significantly more corrosion than their solid counterparts. The $I_{corr}$ values of all of the wire types in iron chloride were significantly greater than all wires in artificial saliva. Pitting corrosion was present in the twisted wires in artificial saliva and all types of wires in iron chloride solution.

Conclusion: Twisted wires display a greater corrosion rate than solid wires of the same composition. Crevice conditions produce significantly greater corrosion rates as well. Clinicians should be aware of these differences when choosing a wire for a fixed retainer.
ACKNOWLEDGEMENTS

Tara L. Groen, DMD

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

The final phase of orthodontic treatment is retention. Once teeth are aligned, they must be passively held in their final position to allow for healing of the tissues that are rapidly adapting during orthodontic tooth movement – the alveolar bone, periodontal ligament and supporting gingival tissues. This healing phase generally lasts for 12 months after active orthodontic treatment has ceased. However, terminating retention at the 12-month mark may still result in relapse – a return of the teeth to their position before orthodontic treatment. There are many potential factors that may cause relapse once retention has ended, including soft tissue pressures from the lips and tongue, and iatrogenic causes such as overexpanding dental arch forms (Graber et al., 2017). One of the most important factors influencing relapse is continued growth of the jaws after orthodontic treatment.

It is widely accepted that differential growth of the jaws is a main contributor to relapse. In accordance with the cephalocaudal gradient of growth, the mandible generally continues to grow later and longer than the maxilla. This late growth of the mandible predisposes the mandibular incisors to relapse into a crowded position. Even patients who undergo orthodontic treatment as adults, who have minimal facial growth remaining, regularly experience lower incisor crowding (Proffit et al., 2013). These observations contradict the original view of orthodontic stability put forth by Edward Angle, who believed that relapse would not occur if teeth were placed in an ideal occlusion. A more current view of retention is explained by Nanda & Nanda, who relates the consistent changes in the alignment and occlusion of the teeth to the normal changes brought about
by the aging process of the rest of the body and states the only way to achieve long-term stability is to provide patients with long-term retention (Nanda & Nanda, 1992).

**Fixed retainers**

In accordance with the acceptance of long-term retention, many orthodontists utilize fixed retainers – a segment of wire bonded to the lingual surfaces of the anterior teeth. Some clinicians choose to use fixed retainers in clinical situations with a higher propensity toward relapse, while others choose to use them routinely (Graber et al., 2017). Benefits of bonded retainers include circumventing the potential problems related to patient compliance that arise with removable retainers – such as loss or breakage of the removable retainers, or simply forgetting to wear the removable appliance for the prescribed hours per day. Patients may prefer fixed retainers over removable retainers because of their hands-off nature, and the fact that they are not visible during smiling or talking (Axelsson & Zachrisson, 1992). Fixed retainers can also remain in place for many years – it has been reported that 98.9% of mandibular and 97.6% of maxillary fixed retainers were still in place after 10 to 15 years of follow up (Kocher et al., 2019). A commonly cited downfall of fixed retainers is their hindrance to good oral hygiene – a problem not generally encountered with removable retainers. Eroglu et al. refutes this idea, however, finding no significant differences in plaque indices, bleeding on probing and probing depths in patients with fixed retainers, Hawley retainers or clear vacuum-formed retainers (Eroglu et al., 2019).

Fixed retainers generally consist of a 0.028 to 0.032-inch solid wire or a 0.0195 to 0.0215-inch multistranded wire bonded to the lingual surfaces of the incisors. The solid
wire is typically bonded to the mandibular canines only, while the middle portion of the wire rests just above the cingula of the incisors. A multistranded wire can be bonded to the mandibular canines and all incisors, or the four maxillary incisors (Zachrisson, 2015).

The bonding protocols differ between the two wire types because of their relative stiffnesses. A solid wire of a certain diameter has a greater stiffness than does a multistranded wire of the same diameter (Graber et al., 2017). The length of the wire segment between the points of adhesion to the tooth surface also has a great impact on the stiffness of the retainer – a shorter length of wire of a certain diameter is stiffer than a longer length of wire of the same diameter. It is desirable for a fixed retainer wire to be stiff enough to resist the movement of the teeth toward relapse, but the wire must not be too stiff to prevent the teeth from exhibiting their physiologic movements during function. If the fixed retainer exceeds this stiffness, the forces during normal function will cause breakage of the retainer (Zachrisson, 2015). If a solid wire is used for the fixed retainer, there must be a longer span of wire between bonding points to allow for physiologic movement of the incisors; therefore, solid wires are bonded to the canines only. A multistranded wire, being less stiff than a solid wire, cannot resist the forces of relapse if it is not bonded to multiple teeth along its span to increase its stiffness.

The choice between wire types and bonding protocols is at the discretion of the clinician, as there is no official retention protocol available (Graber et al., 2017). The clinician may consider many factors when choosing between a solid or multistranded wire for a fixed retainer, including the rate of debonding and wire breakage, the effectiveness in maintaining the alignment of the incisors, and the ease of oral hygiene. It has been found that solid wires detach from the teeth less frequently and also experience
fewer fractures than multistranded wires (Störmann & Ehmer, 2002; Al-Nimri et al., 2009). However, multistranded wires are significantly more effective at maintaining incisor alignment (Al-Nimri et al., 2009). Renkema et al. reported 90% of patients with a multistranded wire retainer to have perfect alignment of lower incisors after 5 years of retention. Patients with relapse experienced only 0.8 mm of relapse, on average. This relapse was observed in patients with bond failures (Renkema et al., 2011). Plaque accumulation increases for teeth in contact with a fixed retainer, but the type of fixed retainer does not affect the amount of plaque accumulated (Störmann & Ehmer, 2002).

Beyond choosing a solid or multistranded wire, clinicians have many options in terms of the material of choice for a fixed retainer. Due to the lack of a generalized retention protocol, clinicians choose a wire for a fixed retainer based on clinical experience, cost of the material or a host of other factors. Available materials for fixed retainers include stainless steel, cobalt-chromium alloys, beta-titanium alloys, gold-plated alloys and more. An important, yet often overlooked, matter is the corrosion behavior of the material of choice for a fixed retainer.

**Corrosion of orthodontic alloys**

When orthodontics was introduced as a dental specialty, alloys of precious metals such as gold were used for all orthodontic purposes. As stainless steel was introduced in 1929, precious metal alloys no longer held a place in orthodontics (Proffit et al., 2013). Stainless steel, as compared to precious metal alloys, had greater strength and better resistance to corrosion. Currently, type 304 stainless steel, consisting of 18-20% chromium, 8-10% nickel, a small amount of carbon, and a balance of iron, is most
frequently used (Castro et al., 2015). The chromium reacts with oxygen in the environment to create a passive surface, and nickel stabilizes the austenitic structure of the steel (Kusy, 1997).

Shortly after the advent of stainless steel, Elgiloy, a cobalt-chromium alloy, was developed. An alloy of 40% cobalt, 20% chromium, 16% iron, 15% nickel, and other elements, it had a stiffness like that of stainless steel, but had increased formability. In later decades, beta-phase titanium alloys were introduced. These alloys contained 80% titanium, 11.5% molybdenum, 6% zirconium and 4.5% tin (Kusy, 1997). Stainless steel, cobalt-chromium and titanium alloys all form a passive surface oxide film to resist corrosion (Castro et al., 1995).

Corrosion is an electrochemical process that results in the destruction of a metal. Corrosion consists of two reactions – oxidation at the anode and reduction at the cathode. The anodic reaction is the one of interest, as this is the reaction that dissolves the metal atoms, displacing them in the form of ions to the surrounding environment. The environment of the oral cavity is constantly being bathed in saliva, a complex fluid containing dissolved electrolytes and enzymes. Although saliva acts as a buffer, ingested foods and drinks can create an acidic environment. The electrolyte-rich and acidic environment of the oral cavity predisposes metal alloys to corrosion (Fraunhofer, 1997).

The passive oxide layer on the surface of orthodontic alloys allows them to resist corrosion, but these passive layers can slowly dissolve under certain conditions, exposing the metal ions beneath and allowing them to diffuse into solution. The passive layer is able to reform, but a failure to reform the passive layer may allow the anodic reaction to continue until the metal is significantly degraded. In the case of noble metals, such as
gold, the metal atoms themselves are very stable and do not readily react with elements in their local environment, rendering them more resistant to corrosion (Fraunhofer, 1997).

Many studies have shown that orthodontic alloys readily corrode in oral environments. Kim et al. reported that stainless steel was susceptible to corrosion, whereas a beta-titanium alloy experienced very little corrosion (Kim et al., 1999). Kuhta et al. detected significant amounts of chromium, nickel and iron ions leached from stainless steel wires (Kuhta et al., 2009). It is also known that the presence of fluoride ions in the environment predisposes the alloy to pitting corrosion – a destructive form of corrosion in which the passive layer cannot reform (Barcelos et al., 2013; Fraunhofer, 1997). Crevice corrosion can occur when a nonmetallic material comes into contact with a metal. In the junction between the nonmetal and metal, an oxygen depleted environment forms, preventing the passive oxide layer from reforming, resulting in increased corrosion (Eliades & Athanasiou, 2002). Areas of crevice corrosion may occur where bonding material is applied to the wire of a fixed retainer.

Corrosion of metals is of clinical importance for two reasons – the first being the decay of mechanical properties of the wire. Roughening of the metal’s surface and inherent weakening of the metal can occur with prolonged corrosion, which can ultimately lead to mechanical failure of an orthodontic appliance (Castro et al., 2015). Failure is more likely to occur in the dual presence of repeated mechanical loading of the appliance and corrosion (Fraunhofer, 1997). For appliances designed to function in the mouth for upwards of 10 years, minimizing corrosion is an important goal in ensuring the longevity of the appliance. The second reason to consider the corrosion of metals in orthodontic appliances is the potential biological effect on the patient.
**Biocompatibility**

As the metals in orthodontic appliances corrode, metallic ions are released into the oral cavity, and these metallic ions may affect the tissues of the patient. Biocompatibility refers to the ability of a material to perform as intended within a body system without spurring clinically significant adverse effects (Schmalz, 2014). The biocompatibility of orthodontic brackets, bands and archwires has been studied extensively. On average, these appliances are present in the oral cavity for two to three years. As noted before, fixed retainers can remain in the mouth for a much longer duration – and yet, few studies have been published regarding the biocompatibility of fixed retainer wires.

The biocompatibility of an alloy depends upon its composition of individual metals, and the level at which it corrodes – the amount of metal ions displaced from the material itself to the environment of the oral cavity. To determine the effects of these metal ions on biologic systems, researchers can measure cytotoxicity, the level of cellular damage, or genotoxicity, the presence of DNA damage in the form of chromosomal breakage or gene mutation. Research has linked nickel and chromium ions specifically to these negative biological effects (Martín-Cameán et al., 2015).

While a safety threshold of exposure to nickel and chromium has not been established, a European Council Directive classifies nickel and chromium as toxic substances and suggests restricting nickel exposure of the skin to 0.5 µg cm\(^{-2}\) week\(^{-1}\) (Milheiro et al., 2012; Mikulewicz et al., 2012). Generally, studies quantifying nickel and chromium release from orthodontic wires conclude that the levels are below that which would cause a toxic systemic effect but are present in a large enough quantity to produce
an allergic reaction (Milheiro et al., 2012; Kuhta et al., 2009). Case reports of allergic reactions caused by orthodontic appliances exist in the literature (Feilzer et al., 2008). Ağaoğlu et al. conducted a study of the saliva and serum of patients with fixed orthodontic appliances and found a significant increase in the levels of nickel and chromium in serum at 2 years of treatment. While the ion concentrations in serum did not reach a toxic level, long-term effects of the systemic exposure are still unknown (Ağaoğlu et al., 2001).

Several studies show the effects of metal ions on the tissues of the oral cavity. Gursoy et al. found exposure to low levels of nickel caused epithelial cells to proliferate more than controls, potentially linking the nickel release of orthodontic appliances to the gingival overgrowth seen in many patients (Gursoy et al., 2007). Low levels of nickel exposure were also shown to induce apoptosis in oral epithelium cells (Trombetta et al., 2005). Another in vitro study by Rose et al. investigated the survival of fibroblast cell cultures exposed to the corrosion products of different alloys. Severe cytotoxic effects were observed in the cells exposed to a cobalt-chromium alloy. The investigators also evaluated the corrosion rate of each alloy utilizing inductively coupled plasma atomic emission spectroscopy and determined the corrosion rate was positively correlated with the level of cytotoxicity (Rose et al., 1997).

In vivo studies have also demonstrated toxic effects from exposure to alloys. Faccioni et al. harvested buccal mucosa cells from patients undergoing orthodontic treatment. The epithelial cells had a greater concentration of nickel and cobalt compared to cells of control patients, and there was a larger number of apoptotic cells present in the patients with fixed appliances (Faccioni et al., 2003). Fernández-Miñano et al. also took
samples of buccal mucosa epithelium from patients fitted with stainless steel, nickel-free, or titanium brackets. Utilizing a comet assay, it was found that cells in contact with the stainless steel and nickel free brackets experienced DNA damage, whereas the titanium brackets did not have a genotoxic effect (Fernández-Miñano et al., 2011).

While it has been shown that the corrosion products of orthodontic materials do not reach toxic systemic levels, there is evidence that the corrosion of orthodontic appliances can have a biological effect. Furthermore, there is a lack of research on fixed retainers specifically, which can remain in the mouth for much longer periods than traditional orthodontic fixed appliances. Milheiro et al. investigated the nickel release of several commercial brands of stainless steel fixed retainer wires, however, there are several more fixed retainer materials on the market that have not been studied (Milheiro et al., 2013). The objective of this study is to determine the general and crevice corrosion properties of several fixed retainer wires currently on the market. It is hypothesized that the gold-plated stainless steel and beta-titanium retainer wires will experience less corrosion than the stainless steel and cobalt-chromium alloys.
CHAPTER 2
MATERIALS AND METHODS

In this study, 7 types of metal wires commonly used for fixed retention were selected for testing. Three were comprised of stainless steel: Nubryte from Dentsply GAC (Bohemia, NY), a 0.028-inch solid wire; Tri-Flex Twisted Wire from Rocky Mountain Orthodontics (Denver, CO), a 0.0215-inch 3-stranded wire; and Ortho FlexTech from Reliance Orthodontic Products (Itasca, IL), a 0.038-inch braided ribbon. Also from Rocky Mountain Orthodontics, a 0.028-inch solid Blue Elgiloy – a cobalt chromium-based wire – was tested. Two gold-plated stainless-steel wires from Gold’n Braces (Palm Harbor, FL) – Penta Twist, a 0.0215 5-stranded wire and a 0.028-inch solid wire – were used. Lastly, Retainium, a 0.028-inch beta-titanium ribbon from Reliance Orthodontic Products was tested. The solid and multistranded wires are available in several different diameters – these diameters were chosen based on what is common for fixed retainer usage. The stainless steel braided ribbon and beta-titanium ribbon are only available in the sizes listed above. The following table details the compositions of the wires tested.

Table 1. Compositions* of the tested wires, by weight

<table>
<thead>
<tr>
<th>Wire</th>
<th>Iron</th>
<th>Chromium</th>
<th>Nickel</th>
<th>Cobalt</th>
<th>Manganese</th>
<th>Aluminum</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel - Solid</td>
<td>69.8</td>
<td>18.6</td>
<td>8.8</td>
<td>0.2</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stainless Steel - Twisted</td>
<td>65-75</td>
<td>15-20</td>
<td>8-12</td>
<td>0-5</td>
<td>0-2</td>
<td>0-2</td>
<td>-</td>
</tr>
<tr>
<td>Stainless Steel - Braided</td>
<td>12-89.5</td>
<td>10.5-30</td>
<td>0-40</td>
<td>0-1</td>
<td>0-15</td>
<td>0-1</td>
<td>0-1</td>
</tr>
<tr>
<td>Gold Plated** - Solid</td>
<td>67.8-75</td>
<td>17-19</td>
<td>8-10</td>
<td>-</td>
<td>0-2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gold Plated** - Twisted</td>
<td>67.8-75</td>
<td>17-19</td>
<td>8-10</td>
<td>-</td>
<td>0-2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CoCr</td>
<td>16</td>
<td>20</td>
<td>15</td>
<td>40</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beta-Titanium</td>
<td>0-5</td>
<td>0-10</td>
<td>0-0.9</td>
<td>-</td>
<td>-</td>
<td>0-40</td>
<td>50-100</td>
</tr>
</tbody>
</table>

* Compositions are as reported by the manufacturer/vendor
**Compositions of the gold plated wires are of the underlying wire. Both wires are plated with 23+ karat gold with cobalt added
Ten segments of each of the 7 wire types were randomly placed into two groups corresponding to the test solutions used later (n=10 per each wire). Each wire was cut into 5-inch segments, and a 25-mm segment of wire was isolated with nail lacquer. Gold-plated wires were isolated at the plated end of the wire, to assure the sample was completely coated in the gold plating. Each wire was only tested once.

Each type of wire was first tested in Fusayama-Meyer artificial saliva solution, containing 0.4 g/L each of potassium chloride and sodium chloride, 0.6 g/L of calcium chloride, 0.69 g/L of sodium phosphate monobasic dihydrate, and 1 g/L of urea. This test was to determine the general corrosion of each type of fixed retainer wire. New wires were also submersed in a 6% iron chloride solution to determine the effects of crevice corrosion. This solution is frequently used to test the susceptibility of stainless steel and other alloys to crevice corrosion (ASTM G46-94, 2018).

An electrochemical cell set up was utilized for each test. The wire to be tested, a reference electrode (saturated calomel electrode or SCE) and a graphite rod acting as the counter electrode were placed into a lidded beaker. The beaker contained either solution and its lid contained holes in which to place each of the 3 electrodes. The tested wire and other electrodes were connected to leads, or alligator clips, coupled to a potentiostat (Gamry PC4; Warminster, PA).

First, the open circuit potential (OCP), measured in mV, was recorded for 3 hours. Polarization resistance was then measured by scanning potential from -20 mV (vs OCP) to +20 mV (vs OCP) at a scan rate of 0.1 mV/s while measuring the resulting current. Polarization resistance (R_p) in MΩ was calculated utilizing Ohm’s law (R_p=V/I) by measuring the slope of the line when voltage was plotted versus current. Finally, a
potentiodynamic curve was created by cycling potential between -300 and 700 mV (vs OCP) at 1 mV/s while measuring current. Corrosion current (Icorr), measured in nA, was calculated with the Gamry software. OCP at 3 hours, $R_p$, and Icorr were recorded for all tests. It should be noted the corrosion current was measured for each 25 mm long segment of the wire, and not normalized for surface area, because the wires were different diameters and the surface area of the twisted wires is not easily determined. Thus, the current measured represents the amount of current flowing from the length of wire typically used intraorally, rather than a normalized area in contact with solution.

OCP at 3 hours, $R_p$ and Icorr were compared for all of the wires and compared between the two tests – artificial saliva and iron chloride solutions. The data were compared with a two-way analysis of variation (ANOVA), with type of wire and solution as factors, and post hoc analysis with a Tukey test.
CHAPTER 3
RESULTS

The braided stainless steel wire was found to be comprised of many individual links. When this wire is not under compression, the links are not all in uninterrupted contact, and therefore, did not display electrical conductivity. Therefore, this wire type was unable to be tested in the experimental setup. The remaining 6 wire types were tested as described above, and the results consist of the data gathered from these 6 wire types.

Table 2 displays the mean values of open circuit potential (OCP), polarization resistance ($R_p$), and corrosion current ($I_{corr}$) for the artificial saliva test and the crevice corrosion test. To compare wire types, mean values in each column with the same letter (A, B, etc.) are not significantly different ($p > 0.05$). Mean values with multiple letters indicate the value overlaps with two significantly different categories. An A corresponds to the mean value associated with the least corrosion in each measurement.

Table 2. Electrochemical properties of the retainer wires

<table>
<thead>
<tr>
<th>Wire</th>
<th>Artificial Saliva</th>
<th>Iron Chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OCP (mV vs SCE) @ 3 hours</td>
<td>$R_p$ (MΩ)</td>
</tr>
<tr>
<td>Stainless Steel - Solid</td>
<td>182 ± 76 AB</td>
<td>15.1 ± 3.9 A</td>
</tr>
<tr>
<td>Stainless Steel - Twisted</td>
<td>-10 ± 27 DE</td>
<td>2.4 ± 1.4 D</td>
</tr>
<tr>
<td>Gold Plated - Solid</td>
<td>214 ± 81 AB</td>
<td>2.6 ± 0.9 D</td>
</tr>
<tr>
<td>Gold Plated - Twisted</td>
<td>115 ± 32 BC</td>
<td>0.6 ± 0.1 D</td>
</tr>
<tr>
<td>CoCr</td>
<td>-43 ± 119 E</td>
<td>5.5 ± 2.6 C</td>
</tr>
<tr>
<td>Beta-Titanium</td>
<td>59 ± 39 CD</td>
<td>9.1 ± 1.3 B</td>
</tr>
</tbody>
</table>
Figures 1-2 show the OCP of each type of wire in artificial saliva and iron chloride, respectively. The OCP is measured as no current is flowing through the wire and is a general measure of the wire’s capacity to corrode. Lower values signify a higher likelihood to corrode; conversely, greater values indicate greater nobility.

Figure 1. OCP of all wires in artificial saliva from 0-3 hours

Figure 2. OCP of all wires in iron chloride from 0-3 hours
Figures 3-4 demonstrate the polarization resistance of each type of wire in artificial saliva and iron chloride, respectively. Polarization resistance is equal to the slope of the lines plotted in the following figures – a line with a lower slope, or more horizontal line, indicates its corresponding wire type is more likely to corrode.

Figure 3. Polarization resistance of all wires in artificial saliva

Figure 4. Polarization resistance of all wires in iron chloride
Figures 5-10 are representative potentiodynamic curves from each individual wire type in artificial saliva. Potentiodynamic curves graphically display the corrosion behavior of the wire.

Figure 5. Potentiodynamic curve of solid stainless steel wire in artificial saliva

Figure 6. Potentiodynamic curve of twisted stainless steel wire in artificial saliva
Figure 7. Potentiodynamic curve of solid gold plated wire in artificial saliva

Figure 8. Potentiodynamic curve of twisted gold plated wire in artificial saliva
Figure 9. Potentiodynamic curve of cobalt-chromium wire in artificial saliva

Figure 10. Potentiodynamic curve of beta-titanium wire in artificial saliva

Figure 11 shows all artificial saliva potentiodynamic curves superimposed for comparison. Pitting loops can be seen in the twisted wires; pitting is absent in the others.
Figure 11. Potentiodynamic curves of all wires in artificial saliva

Figures 12-17 show the potentiodynamic curves of all wires in iron chloride solution.

Figure 12. Potentiodynamic curve of solid stainless steel wire in iron chloride
Figure 13. Potentiodynamic curve of twisted stainless steel wire in iron chloride

Figure 14. Potentiodynamic curve of solid gold plated wire in iron chloride
Figure 15. Potentiodynamic curve of twisted gold plated wire in iron chloride

Figure 16. Potentiodynamic curve of cobalt-chromium wire in iron chloride
Overall, no single wire type displayed the most or least corrosion in all tests. In the artificial saliva solution, the solid gold plated wire had a significantly (p<0.05) higher
OCP than 4 of the wires, excluding the solid stainless steel wire. The OCP of the solid gold plated wire was higher than the solid stainless steel wire, but not significantly. The solid stainless steel wire had the highest value for $R_p$, which was significantly higher than every other wire tested. The twisted stainless steel, solid gold plated and twisted gold plated wires all had the lowest $R_p$ values – significantly lower than the beta-titanium and cobalt chromium wires. The Icorr value for the twisted gold plated wire was significantly higher than the remaining 5 wires. The twisted stainless steel and the twisted gold plated wires were the only 2 wires to display pitting corrosion in the artificial saliva conditions (Figure 11). The presence or absence of pitting corrosion can be observed in the potentiodynamic curves, and the directionality of the descending curve.

In the iron chloride solution, the beta-titanium wire had the highest OCP, but not significantly higher than the solid gold plated wire. The beta-titanium wire along with the cobalt chromium wire both had the highest $R_p$ in the crevice conditions – significantly higher than the remaining 4 wires. The Icorr values were lowest for beta-titanium, cobalt chromium and solid stainless steel wires – significantly lower than the remaining 3 wires, with the twisted gold plated wire having the highest value – significantly higher than the solid gold plated wire and the twisted stainless steel wire. Pitting corrosion was observed in all 6 wires in the iron chloride solution (Figure 18).
CHAPTER 4
DISCUSSION

Many studies indicate that orthodontic appliances are prone to corrosion in the oral environment. In this study, an *in vitro* laboratory setup was utilized to replicate the oral environment that can be potentially corrosive to fixed orthodontic retainers. Of particular interest was the type of retainer wire – twisted or solid; stainless steel, gold plated stainless steel, beta-titanium or cobalt chromium – and two environments: that of the general oral cavity, and areas of crevice conditions. Data were obtained to determine if there is a difference in corrosion rates among the wire types and the different conditions.

Open circuit potential (OCP) is the electrochemical potential of the wire when no current is flowing, with lower values indicating a higher propensity of the wire to corrode. Polarization resistance ($R_p$) is measured as the current is gradually raised. The slope of the line produced is equal to the $R_p$, with a lower slope indicating more likelihood to corrode. Potentiodynamic curves were utilized to calculate the corrosion rate ($I_{corr}$) and observe pitting behavior. The curve is produced by further modulating the current. As the curve rises, the state changes from cathodic to anodic at a critical point (Esmailzadeh 2018). At this point in the curve, the presence of a passive layer is indicated by a more vertical slope in the curve, as in Figure 5. The curve eventually descends, and the direction it breaks from the ascension indicates if there is pitting activity present. In Figure 5, the descent of the curve follows a leftward path, indicating the absence of pitting corrosion, whereas in Figure 8, the curve breaks to the right, indicating pitting is present.
At the beginning of this experiment, it was hypothesized that the gold plated and beta-titanium wires would experience the least corrosion overall, and that more corrosion would take place within the crevice conditions. The OCP measurements of the wires in both solutions were opposite of the hypothesis – the OCP of all wire types in artificial saliva were lower than the OCP of wire types in the iron chloride. However, both the $R_p$ and Icorr results were consistent with the hypothesis. The artificial saliva $R_p$ values were significantly greater ($p<0.05$) than the iron chloride $R_p$ values, and the artificial saliva Icorr values were significantly lower than the iron chloride Icorr values – indicating that corrosion occurred more readily in crevice conditions.

In terms of the types of wires, no one wire displayed the most or least corrosion in all measurements for both solutions. In artificial saliva, the beta-titanium wire displayed the lowest Icorr, but it was only significantly lower than the twisted gold plated wire. In iron chloride, the beta-titanium wire also displayed the lowest Icorr, but it was not significantly lower than the cobalt-chromium wire. This finding is in agreement with Kim et al., who found that beta-titanium alloys only corrode minimally (Kim et al., 1999). The twisted gold plated wire had the highest Icorr in both the artificial saliva and iron chloride conditions – and both Icorr values were significantly higher than any other wire.

The solid gold plated wire had a lower Icorr value than the solid stainless steel wire in artificial saliva – but it was not significantly lower. In iron chloride solution, the solid gold plated wire had a significantly higher Icorr value than that of the solid stainless steel wire. The twisted gold plated wire had significantly higher Icorr values than the twisted stainless steel wire, in both artificial saliva and iron chloride. These findings directly refute the hypothesis that the gold plated wires would experience less corrosion.
than the other wire types. It was originally hypothesized that the gold plated wires would exhibit less corrosion than the other wire types, due to the nobility of gold. It is possible that the gold plating was not completely continuous around the wire. Microscopic examination of these wires would help to determine the continuity of the gold plating.

The difference in wire configuration – solid or twisted – also seemed to have an effect on corrosion. Firstly, pitting corrosion in the artificial saliva solution was only observed in the twisted wires. It is possible that crevice conditions were created in areas where the multiple strands of the wire came into contact – causing more corrosion overall. In artificial saliva, the Icorr of the twisted stainless steel wire was greater than that of the solid stainless steel wire, but this was not significant. In iron chloride solution, the Icorr of the twisted stainless steel wire was significantly greater than that of the solid stainless steel wire. The Icorr of the twisted gold plated wire was significantly higher than the Icorr of the solid gold plated wire in both artificial saliva and iron chloride. The differences in corrosion rate may simply be due to an overall larger surface area of the twisted wires over the solid wires, however, Milheiro et al. found that nickel ion release from multistranded stainless steel wires was not dependent upon the number of strands of the wires (Milheiro et al., 2012). Another potential explanation for the higher corrosion of the twisted gold plated wire as compared to the solid gold plated wire is the challenge of cohesively plating a twisted wire. If the individual wires were coated prior to being twisted together, the plating may become chipped or scratched during twisting. If the wire is coated after twisting, small areas in tight contact with adjacent wire strands may be difficult to access and not be completely plated. If the plating is not continuous on the twisted wire, there will be small differences in composition along the length of the wire,
promoting higher corrosion rates compared to a solid plated wire that may have a more consistent plating.

As discussed before, multistranded wires are bonded to the teeth at several points along the retainer, creating a greater number of crevice conditions between the wire and composite. In this study, crevice conditions lent themselves to significantly greater corrosion rates, and it was demonstrated that multistranded wires have greater corrosion rates than the solid wires of the same composition. In light of these findings, clinicians should be cognizant that multistranded fixed retainers may corrode more than solid wire fixed retainers for several reasons – more crevice corrosion due to more bonding points, and more corrosion of multistranded than solid wires, both in general and crevice conditions.
CHAPTER 5
CONCLUSION

The corrosion of fixed orthodontic appliances and archwires has been extensively studied, whereas limited studies on the wires used for fixed retainers have been published. It was observed that all types of wires had significantly lower polarization resistance ($R_p$) and higher corrosion rate ($I_{corr}$) in crevice corrosion conditions as compared to artificial saliva conditions. Open circuit potential (OCP) values of all wires in artificial saliva were lower than the values of wires in crevice corrosion conditions. No one wire had the most or the least corrosion in all tests, but the twisted gold plated wire had the highest $I_{corr}$ in both artificial saliva and iron chloride solutions – both of these findings being significant. The beta-titanium wire had the lowest $I_{corr}$ in artificial saliva, but this was not significantly indistinguishable from the twisted and solid stainless steel wires, the solid gold plated wire and the cobalt chromium wire. The beta-titanium wire also had the lowest $I_{corr}$ in iron chloride, but this was not significantly different from the cobalt chromium wire. Based on these findings, orthodontists should be conscious of the potential for fixed retainer wires to corrode, especially in crevice environments, which are more frequent when utilizing multistranded wires for fixed retention.
REFERENCES


