Corrosion of orthodontic temporary anchorage devices

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SUMMARY Corrosion of orthodontic miniscrews or temporary anchorage devices (TADs) has been proposed as a contributor to inflammation, which in turn is a factor in the clinical success of miniscrews. The purpose of this study was to measure the electrochemical properties of orthodontic miniscrews in artificial saliva with and without fluoride. The corrosion properties of three miniscrew products (VectorTAS, Ormco Corp.; Unitek TAD, 3M Unitek; and Through-Hole Screw, American Orthodontics) were tested in an artificial saliva (Fusayama-Meyer) with (1500 ppm) or without fluoride (n = 10/product/solution). Open circuit potential (OCP), polarization resistance (R_{polarization}), and corrosion current (I_{corr}) were measured and statistically analysed with the Friedman/Tukey least significant difference tests. No significant differences (P > 0.05) between miniscrews with regard to OCP, R_{polarization}, and I_{corr} were found except that the American Orthodontics miniscrews had a significantly (P < 0.05) more noble OCP compared to the others. Incorporation of 1500 ppm fluoride in the artificial saliva significantly (P < 0.001) lowered the OCP, reduced the polarization resistance, and increased the corrosion current of each miniscrew product. Few differences existed in the electrochemical properties of miniscrews from the three different manufacturers; however, exposure to fluoride was detrimental to the corrosion properties of all miniscrews.

Introduction

Orthodontic miniscrews or temporary anchorage devices (TADs) have increased in popularity among orthodontists as a means of skeletal anchorage. In an American Association of Orthodontists survey from 2008, 80 per cent of orthodontists have used a TAD in at least one case with the majority of clinicians having 1–3 years experience with TADs (Buschang et al., 2008). Miniscrews are a useful adjunct to traditional anchorage (intraoral or extraoral appliances, teeth) and are used either directly or indirectly for mesial or distal movement of posterior teeth, maxillary incisor retraction, proclination of anterior teeth, and the intrusion of posterior or anterior teeth (Mizrahi and Mizrahi, 2007). Loads are placed on the miniscrew and the material must be able to tolerate that load and remain biocompatible and non-toxic in concert with the expected increase in released elements (Liu et al., 2011). Consequently, commercially pure titanium is used or to increase the fracture resistance of the thin implant, aluminum (Al), and vanadium (V) are incorporated in with Ti to yield a stronger alloy, Ti-6Al-4V (Eliades et al., 2009; Cotrim-Ferreira et al., 2010). Some brands may also contain small amounts of iron (Fe) and manganese (Mn; Iijima et al., 2008).

Failure of the miniscrew is a major concern among clinicians. Failure is a multifactorial problem and most of the current literature shows a success rate of greater than 80% (Reynders et al., 2009; Crismani et al., 2010). Miniscrew mobility and/or loss of anchorage or stability is a typical mode of failure in miniscrews (Luzi et al., 2007). In terms of short- and long-term miniscrew stability, primary stability is affected by the bone mineral density of the surrounding cortical bone, screw type, and screw position (Cha et al., 2010), but extended stability is influenced by new bone growth as miniscrews may be in place for over a year and averaged 74 weeks in one study (Lee et al., 2010). Time in service, extent of osseointegration, and surface features are among the differences between orthodontic miniscrews and conventional dental implants (Crismani et al., 2010); nevertheless, examination of dental implant literature may provide insight into the miniscrew/tissue interaction. Complete osseointegration is not favoured in orthodontic TADs due to difficulty in removal, whereas partial osseointegration would impart stability and resist orthodontic loading. Osseointegration with miniscrews has been observed in animal studies (Vande Vannel et al., 2007), in retrieved miniscrews (Eliades et al., 2009), and in clinical studies (Lee et al., 2010). Peri-implant tissue inflammation has been associated with miniscrews that became mobile or loosen in clinical studies (Miyawaki et al., 2003; Luzi et al., 2009). Although the reasons a miniscrew may induce inflammation are multifactorial and include patient hygiene level, type of surrounding tissue, and miniscrew head design (Tsasoussis and Bauss, 2008), it should be noted that macrophages surrounding failed dental implants have been observed to be loaded with titanium resulting from corrosion (Olmedo et al., 2003). Corrosion...
has been implicated as one of several triggering factors associated with peri-implantitis of dental implants with release of titanium ions considered part of the mechanism underlying the process (Mouhyi et al., 2009). Further reinforcement of this effect occurs because titanium corrosion may be enhanced under inflammatory conditions (Messer et al., 2010), setting up a positive feedback loop of sorts. Similarly, released metal ions play a role in loosening of orthopaedic implants (Cadosch et al., 2009). Further confounding the stability of a given implant, electrical currents arising from the corrosion process will impart electrical potentials that could affect bone cells and subsequent bone deposition/resorption (Gittens et al., 2011).

Fracture of the miniscrew is also a mode of failure observed in clinical studies (Luzi et al., 2009). Although fracture is frequently associated with smaller diameter miniscrews (Miyawaki et al., 2003; Park et al., 2003; Melsen, 2005), it may be conjectured that corrosion may be a confounding factor in the fracture process as has been observed in fractographic analyses of conventional dental implants (Yokoyama et al., 2002). Small pits on the surface of an implant formed from corrosion may amplify the corrosive environment around the implant and compromise its mechanical properties (Gittens et al., 2011). Furthermore, environmental conditions have been observed to affect titanium and its alloys in in vitro fatigue and other stress testing (Könönen et al., 1995; Zavanelli et al., 2000; Yokoyama et al., 2004). Both hydrogen and fluoride have been implicated in affecting these properties. Acidic solutions and fluoride, and especially the combination, decrease the stability of the passive layer typically formed on titanium-based surfaces, thereby decreasing its corrosion resistance. Additionally, hydrogen may induce stress-corrosion cracking via hydrogen embrittlement (Könönen et al., 1995). Apart from reduced mechanical properties, superficially, dental fluoride prophylactic agents have been shown to degrade the surface of titanium (Probster et al., 1992). In miniscrews, some interaction between the implant surface and biological environment has been observed in retrieved TADs (Eliades et al., 2009), implicating that environment does indeed affect miniscrews. Nevertheless, although pits did form on miniscrews exposed to sodium fluoride, it should be noted that miniscrews exposed to fluoridated environments have not exhibited decreased torque or twist angles in a report (Muguruma et al., 2011).

Despite its significance as outlined above, the corrosion properties of orthodontic miniscrews have only been examined in two ion release studies. Morais et al. (2007) detected vanadium and de Morais et al. (2009) observed titanium, aluminum, and vanadium arising from orthodontic mini-implants in remote organs using a rabbit model. In vitro potentiodynamic corrosion experimental methods are a useful adjunct to ion release studies to understand the mechanisms involved in the corrosion process. The objective of this study was to measure the corrosion properties of orthodontic miniscrews in artificial saliva with and without fluoride.

Materials and methods

Three miniscrew products (VectorTAS; Ormco Corp., Glendora, California, USA; Unitek TAD; 3M Unitek, Monrovia, California, USA; and Through-Hole Screw; American Orthodontics, Sheboygan, Wisconsin, USA) were used for corrosion testing in artificial saliva with or without fluoride. The shapes and designs of commercially available miniscrews are varied; these miniscrews had the most similar design among the products of the three companies surveyed. Similarly, 8 mm (thread/body length) miniscrews were selected as it was the largest common size among the selected products. To allow for electrode connection and isolation of only the miniscrews for electrochemical testing, the threaded tip of each miniscrew, up to a standardized 3 mm level, was coated with nail polish and mounted in epoxy resin (Sampl-Kwick; Buehler Ltd, Lake Bluff, Illinois, USA), thus allowing the remainder of the miniscrew towards the collar/head to be exposed to test solution. Electrical connection was established via a steel rod threaded through the resin contacting the tip of the miniscrew and insulated from test solution by a glass tube sealed with sticky wax (Sticky Wax; Kerr Corp, Orange, California, USA). A graphite rod served as the counter electrode and a saturated calomel electrode (SCE; Gamry Instruments, Warminster, Pennsylvania, USA) was the reference electrode. All three electrodes were attached to a computer-driven potentiostat (PC3; Gamry Instruments). Fusayama-Meyer artificial saliva solution (pH = 5.8) of the following composition: KCl (0.4 g/l), NaCl (0.4 g/l), CaCl₂ (0.6 g/l), NaH₂PO₄ (0.690 g/l), and urea (1 g/l) with or without NaF (1500 ppm F⁻) at 37°C was used as the electrolyte; this solution is common in dental implant (Reclaru and Meyer, 1994; Grossoget al., 1999) and orthodontic (Schiff et al., 2004, 2005) corrosion studies. Likewise, although fluoride-containing products contain a range of compositions, 1500 ppm F⁻ from NaF was chosen as it is frequently an ingredient in toothpaste (Twatman et al., 2003) and has been used in dental implant studies (Roselino Ribeiro et al., 2007; Correa et al., 2009).

Electrochemical testing (n = 10/miniscrew product/solution) consisted of three steps. Firstly, the open circuit potential (OCP) was monitored for 2 hours. Next, a linear polarization test, where the current is measured while the potential of the miniscrew is scanned at 0.05 mV/s from −20 to +25 mV (versus OCP), was performed. The outcome of this test was the polarization resistance ($R_p$) which gives a measure of how easily the metal/alloy oxidizes during application of an external potential. Finally, a cyclic polarization scan was conducted between −300 and +700 mV (versus OCP) at a scan rate of 1 mV/s. The corrosion current
(or $I_{corr}$) may be determined with this scan and it gives an indication as to how much a given metal/alloy corrodes. Additionally, cyclic polarization is able to give the breakdown potential, the potential at which a passive layer degrades, and the tendency to exhibit pitting corrosion. In this study, corrosion current was not normalized for surface area as is the conventional practice because, given their design, measuring the surface area of the miniscrews is difficult and isolation of a specific surface area amount on each miniscrew is not feasible. Thus, the measured corrosion current represents the current flowing from a single miniscrew (minus the standardized 3 mm of the tip that is insulated as mentioned above), which represents the clinical situation, i.e. a patient will have a given miniscrew in place regardless if it is slightly larger or smaller than another product.

The OCP at 2 hours, polarization resistance, and corrosion current were analysed with statistical software (SAS version 9.1.3; SAS Institute, Inc., Cary, North Carolina, USA) with manufacturer and test solution as factors. The data were determined to not be normally distributed so the non-parametric Friedman test was used followed by the Tukey least significant difference test for pairwise comparisons when indicated ($P < 0.05$).

Results

Table 1 displays the mean OCP, $R_p$, and $I_{corr}$ values along with the analysis of the Friedman/Tukey LSD tests. Among the three manufacturers, there were no statistically significant differences ($P < 0.05$) between miniscrews with regard to OCP, $R_p$, and $I_{corr}$ except that the American Orthodontics miniscrews had a significantly ($P < 0.05$) more noble OCP compared to the Ormco and Unitek miniscrews. The influence of fluoride on the corrosion properties of the miniscrews was dramatic. Incorporation of 1500 ppm fluoride in the artificial saliva significantly ($P < 0.001$) lowered the OCP, reduced the polarization resistance, and increased the corrosion current of each miniscrew product. Representative potentiodynamic curves for each miniscrew with and without fluoride are shown in Figures 1–3. As the tabular data would suggest, incorporation of fluoride in the artificial saliva had a considerable effect on the potentiodynamic curves. The cyclic polarization curves mostly maintain the same general shape but are shifted to more active potentials (lower on the $y$-axis) and higher currents (towards the right on the log current $x$-axis) when fluoride is added. Additional subtle differences exist among the curves, as will be discussed below. In all cases, pitting loops were not noted for any of the curves, indicating pitting corrosion would not be expected in these solutions.

Discussion

Apart from the OCP values, no significant ($P < 0.05$) differences were noted among the measured corrosion parameters of the miniscrews from the three different manufacturers. This is not surprising given that the miniscrews are composed of the same alloy, Ti-6Al-4V (personal communication with manufacturers). However, a subtle difference did exist in the cyclic polarization curves among the products. The Unitek miniscrew curves exhibited a slightly different shape compared to the Ormco and American Orthodontics curves. Passivity, the formation of a thin, coherent, and continuous oxide layer on the surface of certain metals including titanium, is observed in electrochemical potentiodynamic measurement curves as the relatively vertical trace at potentials more noble than the corrosion potential (shown via a bracket in Figure 1). In other words, the anodic current remains relatively constant despite increased polarization and this is attributed to the protective nature of the passive layer. In artificial saliva, the Ormco and American Orthodontics miniscrews (Figures 1 and 2, respectively) displayed a very stable passive layer, whereas it was less stable in the Unitek miniscrews as observed by the diminished slope and breakdown at approximately 0.2 V (versus SCE). A less stable passive layer typically leads to a greater corrosion rate (Bohni, 2005), and this is observed in the Unitek miniscrew at potentials above 0.3 V (versus SCE).

| Table 1 | Means with standard deviation for electrochemical measurements. AO, American Orthodontics; AS, Artificial Saliva (Fusayama-Meyer solution); LSD, least significant difference; OCP, open circuit potential. |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| OCP (mV versus SCE)            | $R_p$ (MΩ)       | $I_{corr}$ (nA)  |
|                                | AS               | AS w/1500 ppm F$^-$ | AS               | AS w/1500 ppm F$^-$ | AS               | AS w/1500 ppm F$^-$ |
| Ormco                          | 132 (53), Ba     | −448 (146), Bb    | 61.6 (29.2), Aa  | 0.9 (0.2), Ab     | 3.7 (1.7), Aa    | 59.2 (28.2), Ab   |
| Unitek                         | 115 (30), Ba     | −467 (18), Bb     | 68.9 (13.1), Aa  | 0.3 (0.1), Ab     | 2.7 (0.4), Aa    | 197.8 (52.3), Ab  |
| AO                             | 170 (55), Aa     | −314 (79), Ab     | 42.5 (15.8), Aa  | 2.0 (0.4), Ab     | 6.0 (2.2), Aa    | 29.0 (23.9), Ab   |

Friedman/Tukey LSD test analysis: manufacturers (Ormco, Unitek, and AO) with different capital letters denote significant differences ($P < 0.05$) exist for each parameter (OCP, $R_p$, and $I_{corr}$); different lower case letters denote significant differences ($P < 0.001$) exist between specimens tested with/without fluoride in Fusayama-Meyer solution for each parameter.
Figure 1  Potentiodynamic polarization curve of the Ormco Corporation miniscrew in artificial saliva with and without fluoride.

Figure 2  Potentiodynamic polarization curve of the American Orthodontics miniscrew in artificial saliva with and without fluoride.

Consistent with the cyclic polarization observations described above is the different colour appearance of the miniscrews. Surface titanium reacts with oxygen to form a clear oxide, TiO$_2$. However, if the oxide thickness is increased, interaction with light is altered, and the titanium (or alloy) material appears coloured. Common methods to alter the oxide layer thickness include thermal and electrochemical treatments (Abdolldhi et al., 2009). The Unitek miniscrews are silver/grey, whereas the American Orthodontics and Ormco miniscrews are blue and pink coloured, respectively. The silver/grey colour suggests a thinner oxide layer; perhaps not coincidentally, these same miniscrews presented with a less stable passive layer in the cyclic potentiodynamic testing. Any surface treatment to the miniscrews remains proprietary, but the differential colour appearance of the miniscrews suggests different treatments may have been performed on the respective products. It should be noted, however, that some manufacturers offer colour-coded sizes, so not all miniscrews from a given manufacturer may perform as in this report.

Exposure to fluoride had a substantial effect on the corrosion properties of the miniscrews. The OCP of the
miniscrews from all three manufacturers shifted to more active potentials. If other metallic dental materials in the mouth are not similarly affected, alterations in galvanic corrosion currents and susceptibility are possible. For instance, if the Ti-6Al-4V miniscrew is normally cathodic to an amalgam restoration or stainless steel band in saliva, when fluoride is introduced, it is possible that it may then be anodic to the other metal and experience accelerated corrosion. Along this line, Schiff et al. (2005) observed changes in nobility rankings of titanium, stainless steel, and cobalt–chromium orthodontic brackets depending on artificial saliva/fluoride solution. Also detrimental, the corrosion current of the miniscrews increased nearly 5- to 75-fold depending on product. Evaluation of the cyclic potentiodynamic curves yields insight into a factor behind this. Compared to the artificial saliva curves, addition of fluoride affected the integrity of the protective passive layer in all three products as observed by diminished slopes above the corrosion potential (Figures 1–3). The effect was most pronounced in the Unitek miniscrews (Figure 3) as any semblance of a passive region, at least on the potentiodynamic curve, is not present. Previous studies have explored this phenomenon in titanium/titanium alloys (Reclaru and Meyer, 1998; Nakagawa et al., 1999; Schiff et al., 2002; Huang and Lee, 2005). In acidic fluoridated solutions, the F\(^-\) in solution combines with H\(^+\) to form hydrofluoric acid (HF) which is capable of destroying the oxide layer on titanium and its alloys. Soluble titanium-fluoride compounds form, leading to dissolution of the metal. However, the formation of HF may only occur if the pH is below 5 (Nakagawa et al., 1999). In a less acidic (pH = 6) salt solution containing NaF, Huang and Lee (2005) detected soluble Na\(_2\)TiF\(_6\) in a degraded passive layer when the fluoride level reached 1%, leading to lower corrosion resistance in Ti. Some controversy exists as to whether exposure to fluoride is detrimental to titanium if the pH is closer to neutral (Probst et al., 1992; Yokoyama et al., 2004). The pH of the artificial saliva in this study was 5.8 and only decreased to 5.6 with the addition of NaF, yet this was sufficient to affect the miniscrews, supporting Yokoyama et al. (2004) who showed fluoride at more neutral pHs (pH = 6.5) may be a concern too. In terms of clinical recommendations, some authors have advised against using fluoride-containing gels for titanium implants (Schiff et al., 2002), but due to the temporary nature of orthodontic miniscrews, their good success rate, and the risk of decalcification during orthodontic treatment with fixed appliances, the advantages of fluoride treatment (Chadwick et al., 2005) may outweigh the drawbacks outlined above. Still, clinicians should examine the surface of the miniscrews for any noticeable alterations suggestive of excessive corrosion and advise patients accordingly to limit clinical complications.

The clinical implications of this research relate to the direct relation between current flow and ion release. Overall, differences in electrochemical behaviour were more pronounced with environment (presence of fluoride) as opposed to product. The corrosion current of the miniscrews in artificial saliva spanned mean values of 2.7–6.0 nA, which is relatively low and suggests limited ion release in the oral cavity under normal circumstances. Unfortunately, previous studies of elemental release from miniscrews involved measuring ion concentrations in the kidney, liver, and lungs of rabbits after miniscrew implantation in tibias (Morais et al., 2007; de Morais et al., 2009). An oral model could be used for further exploration as well as International Organization for
Standardization (ISO) testing. Alternatively, the increased corrosion rate in the fluoride-containing media implies a significant increase in release of ions. Fortunately, exposure to such conditions via toothpaste, rinses, and gels is usually short-lived, although it should be acknowledged, fluoride may originate from more continual sources such as glass-ionomer cement used to secure a band, etc. Nevertheless, as previously stated, increased corrosion of the titanium-based miniscrews may impact their properties (Könönen et al., 1995; Zavanelli et al., 2000; Yokoyama et al., 2004), and release of elements from the miniscrews has the potential to modify the inflammatory process, increasing the chances of complication or failure (Mouhyi et al., 2009; Messer et al., 2010). The extent of ion release into adjacent tissues would be another critical avenue of study to further investigate local inflammatory responses.

As mentioned previously, the Fusayama-Meyer solution was selected because it is common in dental implant (Reclaru and Meyer, 1994; Grosogote et al., 1999) and orthodontic (Schiff et al., 2004, 2005) corrosion studies. Electrolytes of the Fusayama-type have been regarded to closely resemble natural saliva when testing the electrochemical behaviour of dental alloys and yield results that match clinical observations (Holland, 1992; Ayad et al., 2008). Still, the characteristics of the oral environment are complex and difficult to replicate in any artificial saliva and in in vitro studies in general. Similarly, the concentration of fluoride used in this study was within the range observed in toothpastes reported in clinical studies (Tweetman et al., 2003) and used in dental implant research studies (Roselino Ribeiro et al., 2007; Correa et al., 2009). However, in the clinical situation, the miniscrews may be exposed to a variety of amounts and forms of fluoride-containing agents, including sodium fluoride, sodium monofluorophosphate, stannous fluoride, or amino fluoride, that may impact their electrochemical response. Although influenced by pH, increased fluoride levels would be expected to increase corrosion rates (Nakagawa et al., 1999) and the different forms of fluoride may differentially alter corrosion resistance (Schiff et al., 2005). Additionally, in this study, only 3 mm of the tip of each miniscrew was isolated from the test solution. A miniscrew in clinical use will interface with hard and soft tissue as well as a variety of solutions including saliva, blood, interstitial fluid, and beverages as well as dental-related pastes, rinses, or gels. These yield distinct and sometimes isolated and transient environments that differ from those in this research. Thus, caution is suggested in transferring these results to the clinical situation.

Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Miniscrews from three manufacturers generally exhibited similar corrosion properties in artificial saliva.
2. Exposure to fluoride significantly decreased the OCP, reduced the polarization resistance, and increased the corrosion current of the miniscrews by impacting the integrity of the surface passive layer.

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References


