

Corrosion of orthodontic appliances—should we care?

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Contemporary orthodontics relies on various bonded attachments, archwires, and other devices to achieve tooth movement. These components are composed of varying materials with their own distinctive physical and mechanical properties. The demands made on them are complex because they are placed under many stresses in the oral environment. These include immersion in saliva and ingested fluids, temperature fluctuations, and masticatory and appliance loading. The combination of these materials in close proximity and in hostile conditions can result in corrosion. Our purpose in this article was to consider the literature to date with regard to potential mechanical, clinical, and health implications of orthodontic corrosion. (*Am J Orthod Dentofacial Orthop* 2008;133:584-92)

The corrosion of orthodontic appliances in the oral environment has concerned clinicians for some time; this concern is focused around 2 principal issues: whether corrosion products, if produced, are absorbed into the body and cause either localized or systemic effects; and what the effects of corrosion are on the physical properties and the clinical performance of orthodontic appliances. Our purpose in this review article was to consider the evidence on these issues.

Corrosion occurs from either loss of metal ions directly into solution or progressive dissolution of a surface film, usually an oxide or a sulphide. Whereas some metals are noble and virtually inert, eg, gold and platinum, this is not the case for the metals commonly used in orthodontics.

Essentially, corrosion occurs from 2 simultaneous reactions: oxidation and reduction (redox). Using iron in a weak acid as an example, the oxidation (anodic) reaction results in dissolution of the iron as ferrous ions are produced ($\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$). Reduction occurs at the cathode, with hydrogen ions reduced to hydrogen gas ($2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$). This corrosion process continues until the metal is totally consumed, unless the

metal can form a protective surface layer (passivation), or until the cathodic reactant is consumed (eg, exhaustion of dissolved oxygen in solution). The level of corrosion of any metal depends on the chemistry of the solvent in which it is immersed.

The stainless steel, cobalt-chromium, and titanium alloys used in orthodontic appliances rely on the formation of a passive surface oxide film to resist corrosion. This protective layer is not infallible; it is susceptible to both mechanical and chemical disruption. Even without disruption, oxide films often slowly dissolve (passivation) only to reform (repassivation) as the metal surface is exposed to oxygen from the air or the surrounding medium. Acidic conditions and chloride ions can accelerate the passivation process. Therefore, a diet rich in sodium chloride and acidic carbonated drinks provides a regular supply of corrosive agents. Another contributor to acidic oral conditions is fluoride-containing products, such as toothpaste and mouthwash. Many laboratory studies have demonstrated that, in a fluoridated, acidic environment, the corrosion susceptibility of certain metals, especially titanium, is increased.^{1,2} In these circumstances, the highly protective titanium-oxide film is breached, permitting corrosive attack of the underlying alloy. Schiff et al¹ compared the corrosion resistance of 3 types of orthodontic brackets (stainless steel, cobalt-chromium, and titanium) when placed in a reference solution of artificial saliva and 3 commercially available fluoride mouthwashes (each with similar pH values of about pH 4.3). The corrosion potential and the corrosion current density were measured over a 24-hour period, and the polarization resistance values were calculated. The material with optimal electrochemical properties in artificial saliva was titanium, followed by cobalt-chro-

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mium and stainless steel. All 3 mouthwashes had little effect on the cobalt-chromium brackets, but the stannous fluoride in 1 mouthwash caused considerable corrosion of the stainless steel and titanium brackets. This was due to destruction of the protective oxide layer and was confirmed by scanning electron microscopy (SEM) and analysis of the released ions.

More relevant, perhaps, were the results of an in-vivo study of the sensitivity of titanium brackets to the corrosive influence of fluoride-containing toothpaste and tea.³ In this study, 18 patients undergoing fixed appliance therapy were bonded with titanium brackets on the left side of the mouth and stainless steel brackets on the right side. The authors noted that all patients were right handed, and, therefore, a cross-mouth study might have been a more appropriate design. Fifteen patients were asked to brush with a fluoride gel (pH 3.2), and the other 3 used a fluoride-free paste (pH 9.1-9.7), for 3 minutes twice a day. The patients also kept a dietary record, noting especially foods containing fluoride—eg, tea. After 5.5 to 7 months, 2 titanium brackets and 1 stainless steel bracket were removed and examined for pitting and roughness under SEM. Microscopic evaluation showed no significant difference in the pits and crevices on the surfaces of the brackets, whether or not fluoride paste was used. The difference in the results between this in-vivo study and other laboratory studies might be the exposure times. Although the titanium-oxide protective layer undergoes degradation at pH of 3 and below, saliva, water, and food in the oral environment can dilute the fluoride ion concentration, keeping the pH above this critical level at which corrosion takes place. Therefore, clinically, the role of fluoride in the corrosion of orthodontic appliances might not be as important as suggested by the in-vitro studies. Even if it does occur to some extent, as shown in a laboratory study by Strietzel,⁴ in which the corrosion of titanium by fluoride-containing gels occurred at pH of less than 4, the corresponding corrosion product, titanium tetrafluoride, is known to be an ideal medium for the remineralization of enamel.⁵

Types of corrosion—the chemical and physical processes

Uniform attack is the most common form of corrosion; it affects all metals, although at differing rates. The metal undergoes a redox reaction with the surrounding environment, and it can be undetected until much of the metal is affected.

Pitting and crevice corrosion can form on the surfaces of as-received orthodontic wires and brackets, because they are not perfectly smooth. At a micro-

scopic level, they can exhibit many pits and crevices. These features are thought to increase the susceptibility to corrosion because of their ability to harbor plaque-forming microorganisms.^{6,7} These microorganisms cause localized reduction in pH and depletion of oxygen, which in turn affect the passivation process.⁸ Hunt et al,⁷ in their in-vitro study, demonstrated that polishing nickel-titanium (Ni-Ti) wires to a uniform finish reduced the corrosion rate. However, more recent evidence from Huang⁹ suggests that the link between the surface roughness of as-received archwires and the increased corrosion potential is not straightforward. This in-vitro study investigated the variation in corrosion potential of a number of commercially available Ni-Ti wires using a linear polarization test in acidic artificial saliva (pH 6.25). In addition, SEM and atomic force microscopy were used to assess the surface morphology and the roughness of the wires. Chemical analysis of the passive film was performed by electron spectroscopy. The results showed that the passive films on all wires were essentially the same. However, although the surface roughness of the wires differed significantly, it did not correspond to the corrosion resistance. It was suggested that surface residual stress produced during the manufacturing process might be more important than surface roughness in the susceptibility of the wires to corrosion.

Crevice corrosion can also occur in removable appliances when wires or components of expansion screws enter the acrylic. A brown discoloration can appear beneath the acrylic surface in contact with the metal. This is thought to be due to bacteria and a surface biofilm between the wire and the acrylic, leading to crevice corrosion of the metal.¹⁰⁻¹²

Galvanic corrosion occurs when 2 metals are joined together and placed in a conductive solution or an electrolyte. The more electronegative of the metals becomes the anode, and the more electropositive or the noble metal becomes the cathode. Thus, the more electropositive metal corrodes preferentially. Essentially, galvanic corrosion cells are created because of differences in electrochemical potential between the 2 types of metal or the same metal at different sites. These galvanic cells can also be created under other circumstances, such as differential pH, differences in surface finish (roughness), and work hardening due to repeated bending.

In orthodontics, galvanic corrosion might occur where 2 dissimilar metals are joined in the construction of a bracket or a posted archwire. In the case of removable appliances, the 2 metals can also contribute to galvanic corrosion, but the situation is exacerbated by a soldered joint. This is because the soldered joint is

mechanically active, making it even more susceptible to corrosion.¹³ With soldered wires, the greatest problem is the release of iron, zinc, copper, and, particularly, cadmium ions; the last 3 are released from the cadmium-containing silver solder.¹⁴ In another in-vitro study with fibroblasts to assess potential cytotoxicity, various orthodontic components were tested, both new and used. Only the used stainless steel molar band with its soldered buccal tube demonstrated potential cytotoxicity.¹⁵ This effect was possibly due to the silver and copper brazing alloys used, as was noted previously by Grimsdottir et al.¹⁶

Stainless steel is particularly susceptible to *intergranular corrosion* during brazing and welding; this can occur at temperatures as low as 350°C. Heating leads to the reaction of chromium with the carbon in the steel to form chromium carbide. Subsequent precipitation of this carbide at grain boundaries and slip planes has 2 effects: (1) the alloy becomes more brittle due to slip interference, and (2) the alloy is less resistant to corrosion, because the chromium was used up in the reaction to form the carbide, making less available to form the passive oxide layer.¹⁷

Fretting corrosion occurs in areas of metal contact subject to sustained loads. An orthodontic example is the archwire/bracket-slot interface. During the application of a load, the 2 metals undergo a process of cold welding from the pressure at the interface between them. Continued application of force at such an interface eventually causes the welded junction to shear, disrupting the protective surface oxide layers and leaving the metals susceptible to corrosion.

Whenever an archwire is ligated to orthodontic brackets, the reactivity of the metal alloy increases at sites of stress due to loading; this is called *stress corrosion*. An electrochemical potential can therefore be created along the wire, with some sites acting as anodes and other as cathodes, thus facilitating corrosion.

Metals generally have an increased tendency to fracture under repeated cyclic stressing (fatigue). This phenomenon is accelerated if the alloy is also exposed to a corrosive medium; this is called *corrosion fatigue*. For example, corrosion fatigue might occur when orthodontic wires are left in the oral environment for long periods under load. However, in a study investigating corrosion fatigue of Ni-Ti, titanium molybdenum, and stainless steel wires, none showed increased corrosion as a result of mechanical and electrochemical stressing.¹⁸

Microbiologically influenced corrosion is also possible. Microorganisms and their by-products can affect metal alloys in 1 of 2 ways: (1) certain species absorb

and metabolize metal from alloys, leading to corrosion; and (2) the normal metabolic by-products of other microbial species can alter environmental conditions, making them more conducive to corrosion—eg, by increasing the local acidity levels. The corrosive effects of microbials have been demonstrated in restorative dentistry with dental alloys,¹⁹ particularly endodontic silver points.²⁰ The corrosion products themselves might increase the resistance of some bacteria to antibiotics. Certainly, it is known that the characteristics of some resistance systems in these organisms are shared. An increase in metal resistance in 1 organism can lead to increased antibiotic resistance, which might then be transferred to another bacterial species. Therefore, there is considerable potential for increased exposure to metals and their corrosion products to result in the spread of resistant genes between bacteria, including into pathogens of medical and dental significance.

Manufacturing implications

Manufacturers are well aware of the susceptibility of orthodontic alloys to the various forms of corrosion and have taken steps to combat this potentially destructive process, including the following.

1. Alloy substitution or addition. The addition of certain metals to an alloy can reduce its susceptibility to corrosion. This fact has been used in the production of Ni-Ti and stainless steel orthodontic components.

The corrosion resistance of Ni-Ti orthodontic components is due to the large amount of titanium, usually from 48% to 54%. Titanium can form several oxide configurations (TiO, TiO₂, and Ti₂O₃); titanium dioxide is the most stable and commonly formed oxide.

In the case of stainless steel alloys, the addition of chromium and nickel imparts corrosion resistance. The chromium contributes to the surface oxide layer, which spontaneously undergoes passivation and repassivation in air and the oral environment. The nickel aids corrosion resistance by competing with the chromium to form salts, making more chromium available for passivation.²¹ Oxygen is necessary to initiate and maintain the oxide film, whereas acidic conditions enhance its breakdown. The addition of molybdenum to American Iron and Steel Institute 316L-type stainless steel has been shown to reduce the amount of pitting and crevice corrosion.⁸ Although stainless steel has a passive oxide coating from the chromium, this layer is not as effective as that produced by titanium oxide in Ni-Ti components. Steel therefore has

inferior corrosion resistance when compared with Ni-Ti alloys.

The use of brazing alloys in the fabrication of orthodontic brackets can also lead to corrosion through galvanic action. This can be dramatically reduced by laser welding, rather than brazing, the body of the bracket to its base.²²

2. Coatings. Orthodontic archwires and brackets can be coated with either titanium nitride or an epoxy resin. The former is used to improve hardness and reduce friction; the latter improves esthetics. An in-vitro study to compare these 2 coatings on Ni-Ti wires with uncoated Ni-Ti, titanium, and stainless steel wires indicates that corrosion occurs readily in both stainless steel and uncoated Ni-Ti wires.²³ However, for Ni-Ti wires, the breakdown potentials vary depending on the manufacturer. Although the nitride coating did not affect corrosion, the epoxy coating improved corrosion resistance. Kim and Johnson²³ did not consider the clinical observation that the epoxy coating tends to wear off during use, exposing the underlying wire, and this would obviously affect corrosion behavior.

Some commercial brackets are available with a gold finish produced by either electrodeposition of gold or plasma-arc deposition of titanium nitride on the metal surface. Although the effects of these coatings are not fully understood, it is supposed that they improve corrosion and wear resistance of the bracket.²⁴ From the study of Kim and Johnson²³ on wires, it is unlikely that titanium nitride coating will give corrosion resistance to brackets. Hartung et al,²⁵ in an in-vivo experiment, found some evidence of corrosion on titanium-nitride-coated brackets.

3. Modification of the production process. Variations in manufacturing techniques and postmanufacturing finishing and polishing operations can affect the corrosion behavior of brackets. An in-vitro study showed that brackets with essentially the same composition can have significantly different corrosion properties.²⁶ The microstructure of an alloy can affect corrosion, and the microstructure itself is affected by alloying, heat treatment, and cold working. Cold working, for example, occurs during milling and cutting of the bracket slot; this in turn might induce galvanic couples between the worked and the adjacent unworked areas.²⁴ In addition, some manufacturers use different grades of stainless steel for the mesh and the bracket base, and so introduce galvanic couples. Postmanufacturing surface finishing can also affect corrosion behavior. Many manufacturers electropolish their brackets to improve the appearance and reduce corrosion sus-

ceptibility. However, electropolishing can induce galvanic corrosion cells between polished (eg, tie wings) and unpolished areas (eg, bracket slots).

Another method of reducing corrosion of metals during manufacture is to add a corrosion inhibitor to a solution into which the material is placed, resulting in the formation of a protective layer or coating. A similar effect might also occur in the oral environment, with certain salivary proteins, amylase, and γ -globulin forming a biofilm that acts as a corrosion inhibitor.²⁴⁻²⁷ A retrieval study by Eliades et al²⁸ found that Ni-Ti wires become coated by a proteinacious film that masks surface topography. The composition and thickness of this film depended on each patient's oral conditions and the intraoral exposure time. The organic components of the film were found to be amides, alcohols, and carbonates, with other constituents comprising crystalline precipitates of sodium chloride, potassium chloride, and calcium phosphate. The authors hypothesized that the mineralized regions of the film might act as a protective layer, especially under acidic conditions when the corrosion rates of Ni-Ti and stainless steel wires have otherwise been shown to be increased. This might help to explain why the in-vivo behavior of metallic appliances is often superior to the results predicted by laboratory corrosion studies.

Mechanical implications of corrosion

Ni-Ti wires with superelastic and shape-memory properties have revolutionized modern orthodontics. They have enabled treatment to be completed with fewer archwire changes and have permitted patients to go for longer intervals between visits. The shape-memory effect and the superelastic properties of Ni-Ti wires are due to the well-documented austenitic-martensitic phase transformations that occur with alterations in stress or temperature.²⁹ As previously mentioned, acidic fluoridated conditions created by the regular use of fluoride prophylactic agents might cause increased corrosion of orthodontic wires; this in turn can affect their mechanical properties. This hypothesis was tested in an in-vitro study by Walker et al.³⁰ Sections of Ni-Ti and copper-Ni-Ti orthodontic wires with rectangular cross-sections were placed in 2 types of high fluoride-ion concentration gels: Phos-flur gel 1.1% sodium fluoride acidulated phosphate, 0.5% w/v fluoride, pH 5.1 (Colgate Oral Pharmaceuticals, New York, NY), and Prevident 5000 1.1% sodium fluoride neutral agent, 0.5% w/v fluoride, pH 7 (Colgate Oral Pharmaceuticals). Wire sections were placed in plastic vials with the fluoride gel at 37°C for 1.5 hours. The

authors suggested that this would be equivalent to 3 months of 1-minute daily topical application, although they did not disclose how this was determined. The principal outcome measures were elastic modulus and yield strength. The results suggested that both fluoride gels significantly decreased the unloading modulus and the yield strength when compared with the distilled water control. No significant effects were found for the copper-Ni-Ti wires. This might suggest that, clinically, topical fluoride agents can reduce the functional unloading mechanical properties of Ni-Ti wire and contribute to prolonged orthodontic treatment.

It is not unusual for superelastic Ni-Ti archwires to deform or fracture during clinical use. Few studies have investigated whether there is a relationship between these events and the oral environment. Yokoyama et al^{31,32} performed several laboratory studies on the role of hydrogen absorption in the fracture of Ni-Ti archwires in saline and fluoridated environments. These environments might dissolve the protective oxide film of Ni-Ti and allow adsorption of hydrogen, which has a high affinity with titanium. The subsequent formation of brittle hydrides, primarily titanium hydride, is thought to increase the likelihood of wire fracture. In a recent experiment, sections of superelastic Ni-Ti wire were immersed in 0.2% acidulated phosphate fluoride (pH 5.0) for 24 hours. The martensitic transformation temperatures of the wires were determined before the study and after 24 hours. In addition, hardness and tensile tests were conducted. The tensile strength of the wires was found to increase slightly with immersion times of up to 3 hours and then decreased rapidly with longer immersion (1250-600 MPa), after which they remained constant. Fracture of the alloy tended to occur before the martensitic transformations, when the wires had been immersed for more than 6 hours, with fractographs suggesting that fracture began at the outer wire surface. SEM confirmed that surface corrosion had occurred when the samples immersed for 24 hours were compared with the as-received wires. Greater hydrogen adsorption had taken place with increased immersion. It was concluded that, when the amount of hydrogen adsorbed exceeds 200 mass ppm, the tensile strength of the immersed alloy is reduced to the critical stress level of the martensite transformations. Hydrogen embrittlement as a corrosion process appears to be 1 reason for fracture of titanium and its alloys in a fluoridated environment. However, the results of in-vitro studies should be treated with caution. It would be helpful to repeat this experiment with wires that had been subjected to the oral environment, so that the effects of regular low-dose fluoride products such as toothpaste,

mouthwash, and dietary fluoride could be assessed with respect to the tensile strength of the Ni-Ti wires.

Although corrosion has been implicated as a cause of wire fracture, other authors suggest that it might have more to do with the surface finish of the wire produced by the manufacturer. Schwaninger et al⁶ tested the physical properties (bending and flexural) and the surface topography of some Ni-Ti archwires that had been stored in 1% sodium chloride solution for 11 months. Tests were performed at 2-month intervals, starting at month 1. They found no significant difference in the physical properties, but, when the fracture sites were studied with SEM, fracture initiation and propagation sites occurred at the surface pits. Also, the wires that tended to fracture early had more surface defects. The authors concluded that it was not the effects of corrosion that cause early fracture but, rather, the surface defects generated during manufacturing. Therefore, manufacturers should be encouraged to improve the surface quality of their wires.

It would seem that the causes of archwire fracture are multifactorial, with corrosion, surface finish, and work hardening during treatment all as contributors.

Effects of recycling on mechanical properties

Recycling orthodontic wires and brackets was once common, but this practice is no longer recommended in some countries such as the United Kingdom (BOS, Advice Sheet 16). A number of studies have attempted to investigate the influence of repeated exposure and sterilization on mechanical properties.

Lee and Chang³³ tested tensile strength, friction, bending fatigue, microscopic surface appearance, and surface roughness of Ni-Ti wires that had been exposed to artificial saliva for 4 weeks and a similar group that was then sterilized at 121°C at 15 to 20 psi for 20 minutes. Although there was no difference in tensile properties or bending fatigue, there were increases in surface roughness and coefficient of friction in the recycled group. Mayhew and Kusy³⁴ failed to detect a significant difference in the mechanical properties or the surface topography of Ni-Ti wires subjected to various forms of sterilization when compared with untreated wires. Perhaps recycling brackets with brazed bases might be more problematic, since recycling can comprise heat, chemical, and mechanical processes, which could lead to accelerated crevice corrosion of the brazed joint.²⁶

Health implications

Should we be concerned about the release and potential absorption of nickel and other corrosion products? Orthodontic appliances differ from other

medical uses of nickel alloys because they are not implanted; rather, they are placed in the oral environment. Although these appliances might not seem to be in such an intimate relationship with body tissues, the oral environment is considered hostile and potentially corrosive. There has been much interest about whether detectable levels of nickel are released during orthodontic treatment, and, particularly, whether released nickel is detectable in saliva or serum, and whether it has any health effects.

It was suggested that nickel can have carcinogenic, mutagenic, cytotoxic, and allergenic effects.⁸ Thus, there has been a move to publicize possible adverse reactions to nickel and to emphasize patient awareness of its potential dangers. A well-known example of this is Proposition 65, the Safe Drinking Water and Toxic Enforcement Act, in California. It lists nickel, nickel compounds, and chromium as chemicals known to cause cancer, birth defects, and other reproductive harm.³⁵

However, Tomakidi et al³⁶ published an extensive study on the cytotoxicity and genotoxicity of the corrosion eluates from orthodontic materials, using monolayer cultures of immortalized human gingival keratinocytes. The test materials included nickel-free wires and brackets, nickel-containing stainless steel bands and brackets, and expansion screws made of titanium. Each was placed in artificial saliva, according to International Standards Organization 10271, for up to 14 days, and cell cultures were then exposed to eluates with the highest ion concentrations. None of the eluates had acute cytotoxicity, and an assessment of genotoxicity also showed no apparent DNA damage.

Perhaps the most common adverse effect that orthodontists encounter, or are consulted about, is nickel hypersensitivity. There have been many articles on the subject, often isolated case reports. They indicate that, in some instances, nickel-containing orthodontic appliances have caused gingival hyperplasia, labial desquamation, angular cheilitis, swelling, and burning sensations affecting the oral mucosa.³⁷⁻³⁹ This inflammatory response is considered an example of type IV hypersensitivity. The incidence of adverse reactions in orthodontic patients was estimated at 1:100, with 85% of these incidents attributable to contact dermatitis, mostly involving the extraoral components of headgear.^{40,41}

However, diagnosing nickel hypersensitivity affecting the oral mucosa is more difficult than on the skin. In the mouth, for example, nickel lesions can be easily confused with those caused by mechanical injury or poor oral hygiene.

Although there is evidence that nickel and its compounds can, at certain concentrations, cause harm

when absorbed, it is not clear whether this readily occurs with orthodontic appliances. It is worth considering how much, if any, nickel and chromium are released during orthodontic treatment. Nickel and chromium are consumed in our diets, with average values of 200 to 300 μg per day for nickel and 280 μg per day for chromium. Significant exposure to nickel and chromium can occur from the atmosphere, drinking water, clothing fasteners, and jewelry.⁴² When considering the role of dental rather than just orthodontic alloys, nickel release has been reported to be about 4.2 μg per day.⁴³ If an assessment of heavy metal loading, and therefore recommended safe levels, is based on our estimated intake of dietary elements, then the additional loading from orthodontic corrosion products is likely to be small. However, due to our limited knowledge of the physical and chemical states of the corrosion products released from dental materials in the oral environment—eg, valency state, particulate matter form, and hapten binding—recommendations can be used only as rough guidelines at best.⁴⁴

There are 3 ways of investigating metal ion release: *in vitro*, retrieval (*ex-vivo* investigation of *in-vivo* aged samples), and *in vivo*. As with many of the corrosion studies previously cited, most are *in vitro*, and this makes the results and conclusions potentially irrelevant to the clinical situation. Nevertheless, these studies must be considered, because there are few alternatives.

Some studies have suggested that no nickel is released during intraoral placement of orthodontic appliances. Eliades et al⁴⁵ investigated nickel released from stainless steel and Ni-Ti wires retrieved after clinical use and compared them with as-received wires. The test wires were all of 0.016 \times 0.022-in cross-sections and had been ligated to stainless steel brackets. In total, 20 stainless steel and 25 Ni-Ti wires were retrieved; the intraoral service period was 1.5 to 12 months. SEM and energy-dispersive x-ray microanalysis were used to assess the elemental composition of the wires. The authors found no significant difference between the retrieved and the as-received wires with respect to nickel-content ratios.

Other *in-vitro* and some *in-vivo* studies confirmed the release of nickel and chromium ions into saliva after fixed orthodontic appliance placement, although the levels were low, far lower than normal dietary intake.^{40,42,46-48} Grimsdottir et al¹⁶ analyzed the quantities of nickel and chromium released into physiologic saline solution over 14 days in a laboratory study. Interestingly, although they also found that negligible levels of nickel and chromium were released from the archwires, high levels were released from a headgear facebow. Facebows contain silver solder, which is

thought to be capable of inducing the formation of galvanic couples, leading to the release of nickel and other metal ions.⁴⁹ However, the skin's reaction to headgear is totally different from the reaction in the oral cavity because of the absence of Langerhans cells. It could be concluded from the high release of nickel from a soldered facebow in this study that the laser-welded facebow might be a better alternative.

Even if nickel and chromium are released during orthodontic treatment, is it taken up by the saliva and, more importantly, by the bloodstream? This was the aim of a cross-sectional study that examined saliva and serum samples from 100 patients.⁴⁸ The subjects (ages, 12-33 years) all had fixed appliances. Saliva and blood samples were collected before the appliances were placed and then 1 week, 1 month, 1 year, and 2 years later. The results showed, in the saliva samples, a detectable increase in nickel and chromium levels in the first month, when compared with the initial and 1-week samples. The levels then decreased by a statistically significant amount at 2 years. To place these results into context, the amounts in saliva were 0.53 to 1.53 ppb of chromium and 4.12 to 11.53 ppb of nickel. These are within the normal ranges and far below average daily dietary intake. The serum samples showed a statistically significant increase in the amount of chromium at 2 years when compared with the other time periods. No differences were found in the amount of serum nickel throughout the study. Interestingly, there was also no correlation between the saliva and the serum levels of nickel over the different periods. This suggests that nickel can be detected in saliva but is not absorbed into the bloodstream. A criticism of this study is that the samples were taken from various patients during the study period and not from the same cohort. Because of other factors—eg, previous allergic history and differences in dietary intake of nickel and chromium—it would seem that following a cohort of patients throughout their treatment would have given more valid results.

At these low levels of nickel and chromium in saliva, what is the evidence for cytotoxic and hypersensitivity reactions? The cytotoxic effects of various metallic orthodontic devices, including molar bands, brackets, and archwires, have been assessed by using mouse fibroblasts as previously described.^{16,50} The brackets and archwires showed no cytotoxic effect.⁵¹ The lack of cytotoxic effect of Nitinol on human fibroblasts was also demonstrated by Ryhanen et al.⁵²

It has been suggested that nickel-containing jewelry worn from a young age can induce sensitization of prospective orthodontic patients. A clinical study by Greppi et al⁵¹ indicated that most nickel-sensitive people, receiving intraoral exposure from wires with a

high nickel content, had some local hypersensitivity reactions. A more recent retrospective study investigated the roles of age, previous allergic history, and time of exposure to fixed appliances in the etiology of nickel hypersensitivity.⁵³ Some of the 48 patients (ages, 10-44 years) in the study exhibited clinical manifestations of nickel hypersensitivity. The results demonstrated that the clinical signs of hypersensitivity were independent of the length of time the subject was exposed to the orthodontic appliance. Also, the patients with these signs were significantly younger than those without signs. The most telling finding was that previous allergic history was the most important factor in characterizing nickel hypersensitivity and not the presence of orthodontic appliances. Another study has indicated that nickel-containing orthodontic appliances have little or no effect on the oral and gingival health of nickel-sensitive patients. This might be because higher concentrations of contact allergens are required to elicit a reaction on oral mucosa than on skin.⁵⁴

The relationship between sensitization by a potential allergen at an early age and the reaction after a later new exposure is not simple. Early contact with suspected allergens can actually result in a diminished chance of allergic reaction later in life. Perhaps orthodontic treatment with nickel-containing components before sensitization to nickel (eg, ear piercing) might lower the incidence of nickel hypersensitivity.^{41,55}

CONCLUSIONS

Although corrosion of orthodontic devices occurs, it does not appear to result in significant destruction of the metallic components or have significant detrimental effects on mechanical properties. Exceptions to this might be soldered joints on removable appliances and facebows, and the brazed joints of some stainless steel brackets.

The literature suggests that metal ions are released during orthodontic treatment, but the level is far lower than that ingested in a routine daily diet. Some patients may well demonstrate nickel hypersensitivity when exposed to nickel-containing alloys; previous nickel sensitivity and the patient's age are the best indicators. This relationship, however, is not entirely clear, and there are even indications that orthodontic treatment can improve the immune system's tolerance to nickel in sensitive people.

The impact of corrosion on orthodontic treatment and the health of our patients is not well understood. Based on the best current evidence, it does not appear to be a process that should cause concern. Future work in more clinically relevant situations will lead to a better understanding of the clinical effects of corrosion.

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