CORROSION BEHAVIOUR OF ORTHODONTIC ALLOYS - A REVIEW

T.P. Chaturvedi, BDS, MDS*

* Incharge, Division of Orthodontics, Faculty of Dental Sciences, Institute of Medical Sciences, Banaras Hindu University, Varanasi

FACULTY OF DENTAL SCIENCES
INSTITUTE OF MEDICAL SCIENCES
BANARAS HINDU UNIVERSITY
VARANASI – 221005, U.P. (INDIA)

Address for correspondence:

Dr. T.P. Chaturvedi
In charge,
Division of Orthodontics
Faculty of Dental Sciences
Institute of Medical Sciences
Banaras Hindu University
Varanasi – 221005, U.P. (India)
Email: tpchaturvedi@rediffmail.com

ABSTRACT

Various types of metallic orthodontic wires and brackets e.g. stainless steel, cobalt-chromium-nickel alloys, nickel-titanium alloys, beta-titanium alloys etc. are used in the treatment of malocclusion. These metals undergo chemical or electrochemical reactions with the oral environment resulting in dissolution or formation of chemical compounds. Under several situations the oral environment is highly aggressive and leads to corrosion. The most favorable archwire material/bracket is the one which is capable of resisting the most extreme conditions that could possibly be encountered in the mouth. Orthodontic alloys must have excellent corrosion resistance to the oral environment, which is highly important for biocompatibility as well as for orthodontic appliance durability. The present article reviews the various aspects of corrosion as well as the biocompatibility of orthodontic wires and devices. It will explore emerging research strategies for probing the biological properties of materials. During orthodontic treatment the use of nickel-free alloys, better corrosion resistance alloys and less use of fluoride containing toothpaste or gel is expected.

KEY WORDS: Corrosion, Orthodontic Wires, Biocompatibility, Nickel Allergy, Dental Alloys.

1. INTRODUCTION

The oral cavity provides an ideal and unique environment for studying the biological processes involving metallic dental aids. Dental materials within the mouth interact continuously with physiological fluids. Oral tissues are exposed to a veritable bombardment of both chemical and physical stimuli, as well as the metabolism of about 30 species of bacteria (the total salivary bacterial count is said to be five thousand million/ml of saliva). Yet, for the most part, oral tissues other than dental tissues remain healthy. Saliva is a hypotonic solution containing bioactonate, chloride, potassium, sodium, nitrogenous compounds and proteins[1]. The pH of saliva varies from 5.2 to 7.8. Teeth function in one of the most inhospitable environments in the human body. They are subject to larger temperature variations than most other parts, coping with ice cold temperatures ($0^{0}C$) through to hot coffee and soup ($60^{0}C$). Corrosion, the graded degradation of materials by electrochemical attack, is of concern particularly when orthodontic appliances are placed in the hostile electrolytic environment provided by the human mouth[2,3]. Factors such as temperature, quantity and quality of saliva, plaque, pH, proteins, physical/chemical properties of solids/liquids food and oral conditions may influence corrosion processes.

Orthodontic wires are formed into various configurations or appliances to apply forces to teeth and move them into more desirable alignment. Various types of wires and brackets are used in the treatment of malocclusion e.g. stainless steel, cobalt-chromium-nickel alloys, nickel-titanium alloys, β-titanium alloys, etc (Table-1)[4]. A ductile wire can be formed into various shapes. As a manufacturing process, the industry uses brazing alloys to join the base and wing components of brackets. Silver based brazing alloys form a galavanic couple that can lead to ionic release of mainly copper and zinc. The main purpose of the present article is to briefly review the corrosion aspects and its effect on orthodontic wires and brackets in oral environments; effect of fluoride gel/toothpaste on orthodontic appliances; nickel sensitivity. Summary of the a few experimental works on the corrosion of orthodontic alloys (*in vitro*) is given in Table-2, which can explore the future research strategies for the corrosion study of orthodontic materials.

1.1 Clinical Significance of Corrosion on Orthodontic Wires

It has been proven that small galvanic currents associated with a corrosive environment are continually present in the oral cavity. As long as metallic dental restorative materials or orthodontic wires are employed, there seems to be little possibility that these galvanic currents can be eliminated[5]. For all practical purposes, the metallic restoration/orthodontic wires cannot be isolated electrically from the tooth. Hence resistance to corrosion is critically important for orthodontic wires because corrosion can lead to roughening of the surface, weakening of the appliances, and liberation of elements from the metal or alloy[6]. Release of elements can produce discoloration of adjacent soft tissues and allergic reactions in susceptible patients[7, 8,9]. Corrosion can severely limit the fatigue life and ultimate strength of the material leading to mechanical failure of the dental materials[10]. Some alloys and metals are resistant to corrosion because of inherent nobility or the formation of a protective surface layer. High noble alloys used in dentistry are so stable chemically that they do not undergo significant corrosion in the oral environment.

1.1.1. Weakening of Appliances:

Fracture of orthodontic appliances is a rare phenomenon, which may affect clinical results. Stainless steel becomes susceptible to intergranular corrosion, which may ultimately weaken the alloy. Tensile strength of the orthodontic silver-soldered stainless steel joints will be affected by corrosion process. Despite the good corrosion resistance of stressed NiTi, breakage of orthodontic wires has frequently been found in clinical studies and subjected to degradation caused by corrosion in the oral environment[11,12,13]. According to Zinelis et al.[14] Ag-based soldering alloys introduce a galvanic couple with stainless steel alloys, inducing release of metallic ions like Cu^{++} and Zn^{++}, the elements most readily leached out from silver solder alloys. This indicates that orthodontic appliances do fail in the short term and require remedial action prior to the completion of the patient treatment cycle. Anisa Vahed et al[15] reported that prolonged exposure in simulated saliva lead to significant reduction in the tensile failure load of silver-soldered stainless joints. The reduction in tensile properties is brought about by a weakness induced by localized corrosion of the solder metal at the solder/wire interface. The preponderance of Cu-rich particles that form in the solder metal at the interface provides a microgalvanic effect that leads to selective dissolution of these particles and corresponding weakening of the interface. Corrosion is the main reason for the progressive dissolution of brazing filler metal, leading to detachment of the wing from the bracket base during orthodontic therapy or at the debonding stage[16].

1.1.2. Sliding Friction

Corrosion increases orthodontic friction force between the archwire/bracket interfaces due to increase in the surface roughness. It results in an inappropriate force distribution on orthodontic appliances and, consequently, the effectiveness of arch guided tooth movement decreases[17,18].

1.1.3. Local Pain / Swelling

Corrosion products have been implicated in causing local pain or swelling in the region of the orthodontic appliances in the absence of infection, which can lead to secondary infection[19].

1.1.4. Cytotoxic Responses

Nickel and chromium induce a type-IV hypersensitivity reaction in the body, and act as a hapten, carcinogen and mutagen. These metals cause several cytotoxic responses including decrease in some enzyme activities, interference with biochemical pathways, carcinogenicity, and mutagenicity[20,21]. Titanium wires containing nickel may cause localized tissue irritation in some patients. Manganese from the alloy is also consumed with saliva which produces toxicity leading to nervous, skeletal disorders, etc. Recent publications have suggested that long term exposure to nickel containing dental materials affect both human monocytes and oral mucosal cells[22,23].

1.1.5 Decalcification of Teeth:

Various acids are formed during the microbial attack on metallic orthodontic appliances in the oral environment. Biofilm forms on the tooth surface with the help of food debris and metabolic products of microbes. Aerobic microbes utilize the simple sugars into the glycolysis process releasing carbon dioxide (CO_2). Generally, the facultative chemoorganotrophs enter into the fermentative pathway utilizing the sugars and produced organic acids, alcohols and CO_2. Chemoorganotrophs in the anaerobic condition, viz Sulphate Reducing Bacteria (SRB), utilize the lactate as carbon source and reduce sulphate into sulphide. Finally, sulphide combines with ferrous ion to form ferrous sulphide as the corrosion product. Ultimately, in the presence of Sulphate Oxiding Bacteria (SOB), sulphide oxidizes into sulphate. In the oral cavity, hydrogen combines with sulphate to form sulphuric acid which is more corrosive in nature. Reduced pH, due to produced acid, influences the decalcification of teeth and corrosion of metallic appliances[24].

1.2. Effect of Corrosion on Orthodontic Wires

1.2.1 Corrosion of Stainless Steel

Orthodontic stainless steel wires are generally made of austenitic stainless steel containing approximately 18% chromium and 8% nickel. This provides a good combination of strength, corrosion resistance and moderate cost. It owes its corrosion resistance property to chromium, a highly reactive base metal. The corrosion resistance of alloy depends on the passive film, which spontaneously forms (passivation) and reforms (repassivation) in air and under most fluid conditions. Oxygen is necessary to form and maintain the film, whereas acidity and chloride ions can be particularly detrimental to it[25]. The presences of soldered joints increase corrosion susceptibility since they have a tendency to emit electrogalvanic currents with saliva and consequently release metal ions. Austenitic stainless steel may loose its resistance to corrosion if it is heated between approximately 400^0C and 900^0C. Such temperatures are within the range used by the orthodontist for soldering and welding. The decrease in corrosion resistance is caused by the precipitation of chromium-iron carbide at the grain boundaries at these high temperatures[26]. Below these temperatures precipitation does not occur and chances of corrosion is less. Corrosion of stainless steel may result due to galvanic cell forming in one or more of the following ways:

i) Surface roughness of stainless wires may cause localized corrosion attack.

ii) Any cut or abrasion of stainless steel by carbon steel pliers/carbon steel bur may act as galvanic cell, and

iii) Brazed or soldered joints in orthodontic appliances can also form galvanic couples *in vivo*.

1.2.2 **Titanium and its Alloys** (cobalt chromium nickel alloys, nickel-titanium alloys, β-titanium alloys):

Titanium is highly corrosion resistant as a result of the passivating effect afforded by a thin layer of titanium oxide that is formed on its surface. The surface roughness of titanium containing alloy is more as compared to stainless steel wires, which may act as galvanic cell in the mouth[27,28,29].

2. Corrosion

2.1. Definition of corrosion

The term corrosion is defined as the process of interaction between a solid material and its chemical environment, which leads to loss of substance from the material, change in its structural characteristics, or loss of structural integrity. Many types of electrochemical corrosion are possible in the oral environment because saliva is a weak electrolyte. The electrochemical properties of saliva depend on the concentrations of its components, pH, surface tension, and buffering capacity. Each of these factors may influence the strength of any electrolyte. Thus, the magnitude of the resulting corrosion process will be controlled by these variables. The features that determine how and why dental materials corrode are oxidation and reduction reactions as well as passivation or the formation of a metal oxide passive film on a metal surface[30].

2.2. Types of Corrosion in Orthodontic Wires

Various forms of corrosion are shown in fig-1 and described as follows.

2.2.1 Uniform Corrosion

A uniform, regular removal of metal from the surface is the usually expected mode of corrosion. It is the most common type of corrosion, occurring with all metals at different rates. The process arises from the interaction of metals with the environment and the subsequent formation of hydroxides or organometallic compounds. For uniform corrosion, the corrosive environment must have the same access to all parts of the surface, and metal itself must be metallurgically and compositionally uniform. Uniform attack may not be detectable before large amounts of metal are dissolved.

2.2.2 Pitting Corrosion

It is a form of localized, symmetrical corrosion in which pits form on the metal surface. It usually occurs on base metals, which are protected by a naturally forming thin film of an oxide. It has been identified in brackets and wires. In the presence of chlorides in the environment, the film locally breaks down and rapid dissolution of the underlying metal occurs in the form of pits. Surfaces of stainless steel and NiTi wire may exhibit crevices and pores which may give rise to attack since they represent sites susceptible to corrosion. Potentiodynamic polarization experiments and scanning electron microscopic oberservations of archwires composed of stainless steel, CoCr, NiCr, NiTi and Beta-Ti exposed to electrochemical corrosion in artificial saliva have shown evidence of pitting corrosion formed on the wire surfaces[31]. Liu[32] studied mechanical characteristics and corrosion behavior of titanium aluminum nitride coating on dental alloys especially in nickel based and chromium based dental materials. They tested corrosion behaviors in 0.9% NaCl solution and observed a higher positive corrosion potential and a lower corrosion current density in alloy having coated with titanium aluminum nitride as compared with uncoated dental alloys. In addition, the pitting corrosion was substantially reduced by the employment of TiAlN coating. Es Souni *et al*[33] found that Cr-Co alloy (Elgiloy) showed high pitting corrosion compared with NiTi alloy, lower repassivation potentials and increase in current density once pitting had occurred. Hera Kim[34] showed that nickel titanium and stainless steel wires were susceptible to pitting and localized corrosion.

2.2.3 Crevice Corrosion

Crevice corrosion occurs between two close surfaces or in constricted places where oxygen exchange is not available. It often occurs through the application of nonmetallic parts of metal (ie, elastomeric ligatures on a bracket). The reduction in pH and increase in the concentration of chloride ions are two essential factors in the initiation and propagation of the crevice corrosion phenomenon. When the acidity of the medium increases with time the passive layer of the alloy dissolves and it accelerates local corrosion process. Crevice corrosion of stainless steels in aerated salt solutions is widely known. Corrosion products of Fe, Cr, and Ni, the main components of stainless steel, accumulate in the crevice and form highly acidic chloride solutions in which corrosions rates are very high[35,36]. Platt *et al*[37] reported that 2205 duplex stainless is an improved alternative to 316L for orthodontic bracket fabrication when used in conjunction with Ti, its alloys, or stainless steel archwires. Rogers[38] showed that by electroplating with gold before and after silver soldering, the stainless steel prevented crevice corrosion.

2.2.4 Fretting and Erosion-Corrosion

The combination of a corrosive fluid and high flow velocity results in erosion-corrosion. The same stagnant or slow-flowing fluids will cause a low or modest corrosion rate, but rapid movement of the corrosive fluid physically erodes and removes the protective corrosion product film, exposes the reactive alloy beneath and accelerates corrosion. Fretting corrosion (type of erosion-corrosion) is responsible for most of the metal release into tissues[39,40]. Conjoint action of chemical and mechanical attack results in fretting corrosion. It occurs in contact areas of materials under load and finds its analogue in the slot-archwire interface of the bracket.

2.2.5 Intergranular Corrosion:

Reactive impurities may segregate, or passivating elements such as chromium may get depleted at the grain boundaries. As a result, the grain boundary and adjacent regions are often less corrosion resistant and preferential corrosion at the grain boundary may be severe enough to drop grains out of the surface. Stainless steel brackets subjected to a range of temperatures, known as sensitization temperatures, undergo an alteration in their microstructure. The phenomenon is due to a precipitation of carbide at the boundaries of the grains[41]. Berge *et al*[42] reported that austenitic stainless steel wires release nickel and chromium in higher amounts than cobalt- chromium wires, resulting in discolouration, rust, or even breakages.

2.2.6 Galvanic Corrosion of Orthodontic Alloys:

It is the dissolution of metals driven by macroscopic differences in electrochemical potentials, usually as a result of dissimilar metals in proximity. When two or more metals or dissimilar alloys (or even the same alloy, subjected to different treatments) come into contact while exposed to oral fluids, the difference between their corrosion potentials results in a flow of electric current between them. In a clinical situation, two dissimilar alloys having different corrosion potentials are often placed in contact such as in orthodontic brackets and archwires. This can cause galvanic corrosion that leads to preferential release of metal ions from the anodic metal or alloy. Surface area ratio of the two dissimilar alloys is a very important factor because it affects the galvanic corrosion behavior. An unfavourable area ratio which consists of large cathode and a small anode, might lead to greater corrosion rate from the anodic alloy. Reed, and Willman[43] demonstrated the presence of galvanic currents in the oral cavity probably first time in detail. Approximate values for the magnitude were established. Burse *et al*[44] described an experimental protocol for *in vivo* tarnish evaluation and showed the importance of proper elemental ratio in gold alloys. Masahir *et al*[45] showed the NiTi alloy coupled with SUS 304 or Ti exhibited a relatively large galvanic current density even after 72 hours. It is suggested that coupling SUS 304-NiTi and Ti-NiTi may remarkably accelerate the corrosion of NiTi alloy, which serves as the anode. The different anode-cathode area ratios used in this study had little effect on galvanic corrosion behavior. Tufekci *et al*[46] described highly sensitive analytical technique which showed the release of individual elements over a month period which appeared to be correlated with micro structural phases in the alloys. Several forms of electrochemical corrosion are based on the mechanism that produces inhomogeneous areas. Failures could be minimized in orthodontic solder joints by employing material couples that minimize galvanic and microgalvanic effects.

2.2.7 Stress Corrosion of Orthodontic Wires:

Stress corrosion occurs because of fatigue of metal when it is associated with a corrosive environment. When arch wire engaged to brackets bonded to crowded teeth, the reactivity status of the alloy increases. The increased reactivity results from the generation of tensile and compressive stresses developed locally because of the multiaxial, three dimensional loading of wire. Thus, an electrochemical potential difference occurs with specific sites acting as anodes and other surfaces acting as cathodes. NiTi orthodontic wires remain in the oral environment for several months and suffer a large number of small loads during mastication. Despite good corrosion resistance of stressed NiTi, the breakage of NiTi orthodontic wires has frequently been found in clinical studies[47]. Wang *et al*[48] studied stress corrosion cracking of NiTi in artificial saliva and demonstrated that the orthodontic NiTi wires were broken by stress corrosion cracking during service. The slight change in temperature will cause the dynamic phase transformation which causes the change in surface state.

2.2.8 Hydrogen damage:

Hydrogen attack is the reaction of the hydrogen with carbides in steel to form methane, resulting in decarburization voids, and surface blisters. It can embrittle reactive metals such as titanium, vanadium, niobium etc.

2.2.9 Microbial Corrosion in Orthodontic Appliances:

Microbiology-related corrosion has been noted in industry for many years. It is widely recognized that microorganisms affect the corrosion of metal and alloys immersed in aqueous environment. Under similar conditions, the effect of bacteria in the oral environment on the corrosion of dental metallic materials remains unknown. Matasa[49] was the first to show evidence of microbial attack on adhesives in the orthodontic field. The effect of enzymatic activity and degradation of composite resins has been reported earlier. Occurrence of these phenomena in brackets results in the formation of craters in the bracket base[50]. Large surface area provide by wire surface provide favorable environment for growth of bacteria. Brushing and attachment of microbes on wire may disturb the passivity of passive metal. The formation of organic acids during glucolysis pathways from sugars by bacteria may reduce pH. A low pH creates favorable environment for aerobic bacteria for corrosion. Microbes oxidize manganese and iron and reaction products viz. MnO_2 FeO, Fe_2O_3, $MnCl_2$, $FeCl_2$ favour corrosion of orthodontic wires. A complex mechanism of interaction occurs amongst anaerobic and aerobic bacteria in various zones, favoring corrosion products. Due to deposition of the biofilm, the metal surface beneath the biofilm and the other areas are exposed to different amount of oxygen, which leads to creation of differential aeration cells. Less aerated zone act as an anode, which undergoes corrosion, releasing metal ions into the saliva. These metal ions combine with the end- products of the bacteria, along with chloride ion in the electrolyte (saliva) to form more corrosive products like $MnCl_2$, $FeCl_2$ etc. favouring further corrosion[51]. Microbial corrosion occurs when the acidic waste products of microbes and bacteria corrode metal surfaces. The incidence and severity of microbial corrosion can be reduced by keeping the area as clean as possible and by using anti-biotic sprays and dips to control the population of microbes. Chang *et al*[50] showed that corrosion behavior of dental metallic materials in the presence of *Streptococcus mutans* and its growth byproducts is increased. Maruthamuthu *et al*[51] studied electrochemical behavior of microbes on orthodontic wires in artificial saliva with or without saliva. According to him bacteria slightly reduce the resistance and increase the corrosion current. Leaching of manganese, chromium, nickel and iron from the wires may be due to the availability of manganese oxidizers, iron oxidizers and heterotrophic bacteria in the saliva.

3. Enhancing oral environment:

In oral environment, fluoride containing commercial mouthwashes, toothpaste and prophylactic gels are widely used to prevent dental caries or relieve dental sensitivity are proper oral cleaning after application of normal brushes with tooth paste. The detrimental effect of fluoride ions on the corrosion resistance of Ti or Ti alloys has been extensively reported. Fluoride ions are very aggressive on the protective TiO_2 film formed on Ti and Ti alloys. Since outermost surface of NiTi archwire contains mainly TiO_2 film with trace amount of NiO, fluoride enhanced corrosion of the NiTi archwires in fluoride containing environment has been considered[52,53]. Fluoride-containing environments can penetrate into the narrow crevices between the orthodontic archwire and bracket in the mouth which is not cleaned out thoroughly. Topical high fluoride concentrations will stay in place and attack the arch wire/bracket interface depending on the fluoride concentration. This may increase friction force between archwire and bracket. Using topical fluoride agents with NiTi wire could decrease the functional unloading mechanical properties of wires and contribute to prolonged orthodontic treatment[54]. Orthodontic patients are required to maintain a high level of oral hygiene, which include regular tooth brushing. *In vitro* studies of effect of tooth brushing showed significant increase in elemental release from nickel alloys when toothpaste was used, however, without toothpaste there is no significant increase in elemental release. There is also evidence to suggest that some mouth rinses may also increase ionic release from silver soldered joints in orthodontic appliances. Schiff *et al*[55] studied corrosion resistance of three types of brackets (cobalt-chromium, iron chromium-nickel and titanium based brackets) in a three fluoride mouthwashes. The result showed that the bracket materials could be divided into two groups: Ti and FeCrNi in one and CoCr, which has properties close to those of Pt. Many studies have shown that fluoride ions can destroy the protectiveness of the surface TiO_2 passive film on Ti or Ti alloy, leading to attacked corrosion morphology, decreased polarization resistance and an increased anodic current density or metal ion release[56]. Furthermore, the corrosion resistance of NiTi decreases on increasing NaF concentration in the artificial saliva. Schiff *et al*[57] studied the corrosion resistance of orthodontic wires in three different commercial mouthwashes and found that the NiTi wires were subject to severe corrosion in Na_2FPO_4 containing mouthwashes. Huang[58] studied surface topography variations of different nickel-titanium orthodontic archwires in different commercial fluoride containing environments. Four tested NiTi archwires had different surface topography variations, depending on the fluoride ion concentration. The archwire manufacturer and emersion environment had a statistically significant influence on surface roughness variation. The increase in surface roughness of NiTi orthodontic archwires in the commercial fluoride containing environments should be taken into account when considering the effectiveness of orthodontic appliances.

4. Nickel Containing Orthodontic Wires:

Nickel containing alloys find extensive application in orthodontics, including metallic brackets, archwires, bands, springs and ligature wires. For most materials, a rough surface promotes corrosion. Doubts remain about biocompatibility of Ni-based alloys when used in dentistry. The use of nickel is of particularly concern since it is the most allergenic of all metallic materials. Not all nickel-allergic individuals will react to intraoral nickel, and it is currently not possible to predict which individuals will react. Because the frequency of nickel allergy is high, it is possible that individuals will become sensitized after placement of nickel containing alloys in the mouth. Nickel is a known allergen[59]. In a study of Finnish adolescents, the prevalence of nickel allergy was found to be 30% in girls and 3% in boys[60]. This was thought to be related to sensitization to nickel by ear piercing as the prevalence in adolescents, with ear piercing it was found to be 31% and only 2% otherwise. Allergic responses are mediated through the immune system. The majority of dental allergies, including responses to nickel containing dental alloys, comprise type IV hypersensitivity reactions, cell mediated by T-lymphocytes. Nickel containing dental alloys can undergo corrosion with release of metal ions[61,62,63]. High content nickel-titanium wires should be avoided in nickel sensitive patients, nickel free alternatives being available for use in such cases[64]. Bishara *et al*[65] studied biodegradation of orthodontic appliances *in vitro* and showed that nickel ions released from orthodontic appliances of nickel- titanium and stainless steel increased over the first week then diminished over time. Gjerdt *et al*[66] studied metal release from heat treated orthodontic wires and demonstrated that heat treatment of the alloys under laboratory conditions increased the release of metal ions-15-60 times. They showed significant initial increase in the concentration and mass of nickel in saliva sample of patient with fixed orthodontic appliances as compared to sampled saliva of patients without orthodontic appliances. Other studies have shown that the release of nickel ions is not proportional to the nickel content of orthodontic wires, but to the nature of the alloys and the method of construction of the appliance. Kerosuo *et al*[67] studied *in vitro* release of nickel and chromium ions from different type of simulated orthodontic appliances. Metal appliances immersed in 0.9% sodium chloride solution showed significantly higher cumulative release of nickel under dynamic (simulated function) compared to static condition. It should be noted that nickel ions released from metallic restorations and intraoral appliances will normally be swallowed and will not accumulate in the oral environment furthermore. The amount of nickel released from dental alloys is significantly less than that consumed orally as part of the dietary intake, although the ingested ions will obviously add to the overall burden of previously nickel sensitized patients. According to Kim[33] for patients allergic to nickel, the use of titanium or epoxy-coated wires during orthodontic treatment is recommended.

Clinical signs and symptoms seen in allergic reactions to nickel include oral oedema, perioral stomatitis, gingivitis, and extraoral manifestations such as eczematous rashes[68,69,70]. The mechanisms of high allergy frequency to nickel are not known, but there is probably genetic component[71,72]. In addition, the tendency of nickel containing alloys to release relatively large amounts of nickel ions probably contributes to their allerginicity. Nickel ions are a documented mutagen in humans, but there is no evidence that nickel ions cause any carcinogenesis intraorally[73]. Galvanic Current or release of ions could account for many types of dyscrasias, such as lichenoid lesions, ulcers, leukoplakia, cancer and kidney disorder, although research has failed to find any correlation between dissimilar metals and tissue irritation. Future steps would be to find correlation between the problems observed in the mouth due to corrosion products and the results of corrosion tests *in vitro*[74]. According to Cioffi *et al*[75] thin layer activation (TLA) method in the biomedical field appears a suitable technique to monitor in real time the corrosion behaviour of medical devices.

5. Summary:

The corrosion of dental materials is a pertinent clinical issue. A primary requisite of any metal alloys used in the mouth is that they must not produce corrosion products that will be harmful to the body. In spite of recent innovative metallurgical and technological advances and remarkable progress in the design and development of surgical and dental materials, failures do occur. One of the reasons for these failures can be corrosion of orthodontic appliances. Corrosion causes severe and catastrophic disintegration of the metal body. Its attack may be extremely localized and cause rapid mechanical failure of a structure, even though the actual volume loss of material is quite small. Surface roughening and deposit build up may have adverse effect on the efficiency of relative wire/bracket movement in orthodontic treatment. Application of fluoride gel containing gel/toothpaste may affect the efficiency of orthodontic appliances. In the future nickel free materials should be expected to be used. Future research is needed regarding material composition influencing corrosion, manufacturing of metallic brackets, influence of various dietary patterns as well as diet substance on corrosion, use of topical fluoride treatment during orthodontic treatment for oral hygiene maintenance.

REFERENCES

1. Martinez, J.R. and Barker, S., Ion transport and water movement. Arch.Oral Biol. 1987, 32, 843-847.
2. Maijer R, Smith DC. Corrosion of orthodontic bracket bases. Am J Orthod Dentofac Orthop. 1982; 81:43–48.
3. Maijer R, Smith DC. Biodegradation of the orthodontic bracket system. Am J Orthod Dentofac Orthop. 1986; 90:195–198.
4. Brantley WA. Orthodontic wires. In: Brantley WA, Eliades T, eds. Orthodontic Materials: Scientific and Clinical Aspects. Stuttgart: Thieme; 2001:77–103.
5. Kenneth J. Anusavice: Phillips' Science of Dental Materials, eleventh edition. SAUNDERS An imprint of Elsevier.
6. Jia W, Beatty MW, Reinhardt RA, Petro TM, Cohen DM, Maze CR, Strom EA, Hoffman M. Nickel release from orthodontic arch wires and cellular immune response to various nickel concentrations. J Biomed Mater Res. 1999; 48:488–495.
7. Dunlap CL, Vincent SK, Barker BF. Allergic reaction to orthodontic wire: report of case. J Am Dent Assoc. 1989; 118:449–500.
8. Greppi AL, Smith DC, Woodside DG. Nickel hypersensitivity reactions in orthodontic patients. Univ Tor Dent *J.* 1989; J3:11–14.
9. Kerosuo H, Moe G, Kleven E. In vitro release of nickel and chromium from different types of simulated orthodontic appliances. Angle Orthod. 1995; 65:2111–116.
10. Iijima M, Endo K, Ohno H, Yonekura Y, Mizoguchi I. Corrosion behavior and surface structure of orthodontic Ni-Ti alloy wires. *Dent Mater J.* 2001; 20:1103–113.]
11. Hunt NP, Cunningham SJ, Golden CG, Sheriff M. An investigation into the effect of polishing on surface hardness and corrosion of orthodontic archwires. Angle Orthod. 1999; 69:5433–440.]
12. Yonekura Y, Endo K, Iijima M, Ohno H, Mizoguchi I. In vitro corrosion characteristics of commercially available orthodontic wires. Dent Mater *J.* 2004; 23:2197–202.

13. Platt JA, Guzman A, Zuccari A, Thornburg DW, Rhodes BF, Oshida Y, Moore BK. Corrosion behavior of 2205 duplex stainless steel. Am J Orthod Dentofacial Orthop. 1997; 112:69–79.

14. Zinelis S,Annouski O, Eliades T, Makou M. Elemental composition of brazing alloys in metallic orthodontic brackets. Angle Orthod 2004;74(3):394-9

15. Anisa Vahed, Nirusha Lachman, Robert D. Failure investigation of soldered stainless steel orthodontic appliances exposed to artificial saliva. Dental materials 2007;23:855-61.

16. Theodore Eliades. Orthodontic materials research and applications: Part 2. Current status and projected future developments in materials and biocompatibility. Am J Orthod Dentofacial Orthop. 2007; 131:253–64.

17. Matasa CG. Orthodontic attachment corrosion susceptibilities. J Clin Orthod. 1995; 29:16–20.

18. Matasa CG. Attachment corrosion and its testing. J Clin Orthod. 1995; 24:16–23.

19. S. Maruthamuthu at al: electrochemical behavior of microbes on orthodontic wires. Current Science, Vol. 89, No. 6, 2005.

20. Pereira ML, Silva A, Tracana R, Carvalho GS. Toxic effects caused by stainless steel corrosion products on mouse seminiferous cells. Cytobios. 1994; 77:73–80.

21. Veien NK, Bochhorst E, Hattel T, Laurberg G. Stomatitis or systemically-induced contact-dermatitis. Contact Dermatitis. 1994; 30:210–213.

22. Al-Waheidi EM. Allergic reaction to nickel orthodontic wire: a case report. Quintessence Int. 1995; 26:385–387.

23. Dunlap CL, Kirk Vincent S, Barker BF. Allergic reaction to orthodontic wire: report of a case. J Am Dent Assoc. 1989; 118:449–450.

24. Christopher M., Brett,A., Ioanitescu,I and Trandafir F., Influence of the biological fluid on the corrosion of the biological fluid on the corrosion of dental amalgam. Corros. Sci.,2004,46,2803-2816.

25. Merritt K, Brown SA. Release of hexavalent chromium from corrosion of stainless steel and cobalt-chromium alloys. J Biomed Mater Res. 1995; 29:627–633.

26. Berge M, Gjerdet NR, Erichsen ES. Corrosion of silver soldered orthodontic wires. Acta Odont Scand 1982;40(2):75-920.

27. Sarkar NK, Redmond W, Schwaninger B, Goldberg AJ. The chloride corrosion behaviour of four orthodontic wires. J Oral Rehabil. 1983; 10:121–128.

28. Grimsdottir MR, Gjerdet NR, Hensten-Pettersen A. Composition and in vitro corrosion of orthodontic appliances. Am J Orthod Dentofac Orthop. 1992; 101:525–532.

29. Oshida Y, Sachdeva RCL, Miyazaki S. Microanalytical characterization and surface modification of TiNi orthodontic archwires. Bio-Medical Materials and Engineering. 1992; 2:51–69.

30. Jacobs JJ, Gilbert JL, Urbani RM. Corrosion of Metal Orhopaedic Implants. J Bone Joint Surg 1988; 80: 1-2.

31. Barret RD, Bishara SE, Quinn JK. Biodegradation of orthodontic appliances. Part I: biodegradation of nickel and chromium in vitro. Am J Orthod Dentofac Orthop. 1993; 103:8–14.

32. G.T. Liu, J.G. Duh, K.H. Chung,J.H.Wang. Mechanical characteristics and corrosion behavior of (Ti,Al)N coatings on dental alloys. Surface & Coating Technology. 200(2005) 2100-2105.

33. Es-Souni M, Fisher-Brandies H On theproperties of two binary NiTi shape memory alloys. Effect of surface finish on the corrosion behavior and in vitro biocompatibility. Biomaterials 2002; 23:2887-94.

34. Kim H, Johnson JW. Corrosion of stainless steel, nickel-titanium, coated nickel-titanium, and titanium orthodontic wires. Angle Orthod. 1999; 69:39–44.

35. Matasa CG. Characterization of used orthodontic brackets. In: Eliades G, Eliades T, Brantley WA, Watts DC, eds. *in vivo-Aging of Dental Biomaterials*. Chicago, Ill: Quintessence. In press.

36. Olefjord I, Wegrelius L. Surface analysis of passive state. *Corrosion Science*. 1990; 31:89–98.

37. Platt JA, Guzman A,Zuccary A Moor Bk. Corrosion behavior of 2205 douplex stainless steel. Am J Orthod Dentofac Orthop. 1997;112:69-79.

38. O.W.Rogers, Brit Dent.J.143 (1977)397-40330.

39. Eliades T, Eliades G, Athanasiou AE, Bradley TG. Surface characterization of retrieved NiTi orthodontic archwires. Eur J Orthod. 2000; 22:317–326.

40. Eliades T, Eliades G, Watts DC. Intraoral aging of the inner headgear component: a potential biocompatibility concern?. Am J Orthod Dentofac Orthop. 2001; 119:300–306.

41. Sutow E. The corrosion behavior of stainless steel oral and maxillofacial implants. In: Eliades G, Eliades T, Brantley WA, Watts DC, eds. In Vivo Aging of Dental Biomaterials. Chicago, Ill: Quintessence. In press.

42. Reed GJ, and willman W: Galvinism in the oral cavity. J Am Dent Assoc 27: 1471, 1940.

43. Burse AB et. Comparison of the in vitro and in vivo tarnish of three gold alloys. J Biomed Mater Res 6;267-277, 1972.

44. Masahiro Iijima; Kazuhiko Endo; Toshihiro Yuasa; Hiroki Ohno;Kazuo Hayashi; Mitsugi Kakizaki; Itaru Mizoguchi. Galvanic Corrosion Behavior of Orthodontic Archwire Alloys Coupled to Bracket AlloysThe Angle Orthodontist: 2005 Vol. 76, No. 4, pp. 705–711.

45. Tufekci E, Mitchell JC at al: Inductively coupled plasma mass spectroscopy measurements of elemental release from 2 high palladium dental casting alloys into a corrosion testing medium. J Prosthetic Dent 87;80-85,2002.

46. Mohlin B,Mullar H, Odman J,Thilander B. Eur J Orthod. 1991;13:386.

47. Jianqiu Wang, Nianxing Li,Guangbin Rao, Enhou Han Wei ke. Stress corrosion cracking of NiTi in artificial Saliva. Dental materials 2007;23; 133-137.

48. Matasa CG. Microbial attack of orthodontic adhesives. Am J Orthod Dentofac Orthop. 1995; 108:132–141.

49. Theodore Eliades, DDS, MS; Athanasios E. Athanasiou, In Vivo Aging of Orthodontic Alloys: Implications for Corrosion Potential, Nickel Release, and Biocompatibility.The Angle Orthodontist*:* Vol. 72, No. 3, pp. 222–237.

50. Jui-Chung Chang, Yoshiki Oshida , Richard L. Gregory , Carl J. Andres , Thomas M. Barco David T. Brown. Electrochemical study on microbiology-related corrosion of metallic dental materials Bio-Medical Materials and Engineering 2003;Volume 13, Number 3 281 – 295.

51. S.Maruthamuthu, A.Rajasekar,S.Sathiyanarayanan,N.Muthukukumar,N.Palaniswamy. Electrochemical behavior of microbes on orthodontic wires. Current Science, 2005 Vol.89; 6, 988-996.

52. Huang HH. Effects of fluoride concentration and elastic tensile strain on the corrosion resistance of commercially pure titanium. Biomaterials 2002;23:59-63.

53. Huang HH, Lee TH. Electrochemical impedence spectroscopy study of Ti-6Al-4V alloy in artificial saliva with fluoride and /or albumin. Dent Mater 2005;21:749-55.

54. Mary P.Walker, Richard J. White, Katherene S. Kula. Effect of fluoride prophylactic agents on the mechanical properties of nickel-titanium-based orthodontic wires. Am J Orthod Dentofacial Orthop. 2005; 127:662-9.

55. Nicolas Schiff, Francis Dalard, Michele Lissac, Laurent Morgan Brigitte G. Corrosion resistance of three orthodontic brackets : a comparative study of three flouride mouthwashes. The European Journal of Orthodontics 2005 27 (6):541-549.

56. Huang HH. Effect of fluoride and albumin concentration on the corrosion behaviour of Ti-6Al-4V alloy. Biomaterials 2003; 24:275-82.

57. Nicolas Schiff, Francis Dalard, Michele Lissac, Brigitte G. Influence of fluoridated mouthwashes on corrosion resistance of orthodontics wires: Biomaterials 2004; 25 (19):4535-4542.

58. Huang HH. Variation in surface topography of different NiTi orthodontic archwires in various commercial fluoride-containing environments. Dental materials 2007; 23:24-33.

59. Bass JK, Fine HF, Cisneros GJ. Nickel hypersensitivity in the orthodontic patient. Am J Orthod Dentofacial Orthop. 1993; 103:280–285.

60. Kerosuo H, Kullaa A, Kerosuo E, Kanerva L, Hensten-Pettersen A. Nickel allergy in adolescents in relation to orthodontic treatment and piercing of ears. Am J Orthod Dentofacial Orthop. 1996; 109:148–154. 25.

61. Park HY, Shearer TR. In vitro release of nickel and chromium from simulated orthodontic appliances. Am J Orthod. 1983; 84:156–169.

62. Staffolini N, Damiani F, Lilli C, Guerra M, Staffolini NJ, Belcastro S, Locci P. Ion release from orthodontic appliances. J Dent. 1999; 27:49–54.

63. Gjerdet NR, Erichsen ES, Remlo HE, Evjen G. Nickel and iron in saliva of patients with fixed orthodontic appliances. Acta Odontol Scand. 1991; 49:73–78.

64. Rahilly G,Price N. Nickel allergy and orthodontics. J Orthod 2003;30:171-174.

65. Bishara SE, Barrett RD, Selim MI. Biodegradation of orthodontic appliances. Part II. Changes in the blood level of nickel. Am J Orthod Dentofac Orthop. 1993; 103:115–119.

66. Gjerdet NR,Hero H. Metal release from heat treated orthjodontic wires. Actaodontol Scan 1987;45:409-14.

67. Kerosuo H, Moe G, Hensten-Pettersen A. Salivary nickel and chromium in subjects with different types of fixed orthodontic appliances. Am J Orthod Dentofac Orthop. 1997; 111:595–598.

68. Hensten-Pettersen A. Nickel allergy and dental treatment procedures. In: Maibach HI, Menne T, eds. Nickel and the Skin: Immunology and Toxicology. Boca Raton, Fla: CRC Press; 1989:195–205.

69. Van Hoogstraten IM, Andersen KE, Von Blomberg BM. et al. Reduced frequency of nickel allergy upon oral nickel contact at an early age. Clin Exp Immunol. 1991; 85:441–445.

70. Jose F. Lopez-A, Jordi M. Angalada, Maria P. Ion release from dental casting alloys as assessed by a continuous flow system : Nutritional and toxicology implications. Dental materials; 22:(2006) 832-837.

71. Lindsten R, Kurol J. Orthodontic appliances in relation to nickel hypersensitivity. A review. J Orofac Orthop. 1997; 58:100–108.

72. Lee YW, Broday L, Costa M. Effects of nickel on DNA methyltransferase activity and genomic DNA methylation levels. Mutat Res. 1998; 415:213–218.

73. Lee YW, Klein CB, Kargacin B. et al. Carcinogenic nickel silences gene expression by chromatin condensation and DNA methylation: a new model for epigenetic carcinogens. Mol Cell Biol. 1995; 15:2547–2557.

74. Claire Manaranche, Helga Hornberger. A proposal for the classification of dental alloys according to their resistance of corrosion. Dental materials (2007) in press.

75. M.Cioffi, D.Gilliland, G.ceccone,R.Chiesa,A.Cigada. Electrochemical release testing of nickel-titanium orthodontic wires in artificial saliva using thin layer activation. Acta Biomaterialia 2005;1 (6) : 717-724.

76. R.A. Zavanelli, G.E. Henriques, I.Ferriera, J. Prosthet.Dent.68(4)1992;692-697.

77. Yukyo Takada,Keisuke N,Kohei K,Osamu O. Corrosion behavior of the stainless steel composing dental magnetic attachments. International Congress series 1284(2005)314-315.

Table 1: Different Types of Wires Used for Orthodontic Treatment and their Composition.

Sl. No.	Type of Wires	Composition
1.	Gold alloys	15-65% Au, 11-18%Cu, 10-25%Ag, 5-10%Pd
2.	Stainless steel	71%Fe, 18%Cr, 08%Ni, C less than 0.2 %
3.	Chrome-Cobalt	40%Co, 20%Cr, 15%Ni, 15.4%Fe, 07%Mo, 02%Mn, 0.4Br, 0.05%Others.
4.	Nickel-Titanium	54-55%Ni, 43-44%Ti, 1.6-3%Co.
5.	Copper- Nickel-Titanium	43Ti, 50%Ni, 0.50%Cr, 6.5%Cu.
6.	Beta-Titanium	79%Ti, 11%Mo, 06%Zr, 04%Sn.

Table 2: Summary of the some experimental work on the corrosion of orthodontic alloys (*in vitro*).

Sl. No.	References	Orthodontics wires	Medium, temperature, pH, period, method etc	Remark
1.	Anisa Vahed *et al*[15]	Stainless steel wire. Silver solder.	Fusayama Meyer artificial saliva. pH- 7 37^0C, 28 days. SEM.	Significant reduction in the tensile failure load of silver-soldered stainless joints. The preponderance of Cu-rich particles that form in the solder metal at the interface provides a microgalvanic effect that leads to selective dissolution of these particles and corresponding weakening of the interface
2.	Berge *et al*[26]	Austenitic stainless steel, Co-Cr wires	Open cell potential measurements	a) Austenitic stainless steel wires release nickel and chromium in higher amounts than that of cobalt-chromium wires, resulting in discolouration, rust, or even breakages. b) Silver solder is less noble metal and thus prone to corrosion.
3.	Liu *et al*[32]	Ni based and Cr based dental materials with Titanium aluminum nitride coating& without coating.	0.9% NaCl Solution Potentiostat	a) Higher positive corrosion potential and a lower corrosion current density in alloy having coated with titanium aluminum nitride as compared with uncoated dental alloys. b) The pitting corrosion was substantially reduced by the employment of TiAlN coating.
4.	Souni *et al*[33]	Cr-Co alloy (Elgiloy) compared with NiTi alloy	Half strength Ringer solution and artificial saliva.	It showed high pitting corrosion, lower repassivation potentials and increase in current density once pitting had occurred.
5.	Hera kim *et al*[34]	Stainless steel, Nitride coated NiTi, and titanium coated orthodontic wires.	0 .9% NaCl solution, Neutral pH, Room temperature. Potentiostat, SEM.	a) SEM Photographs revealed that some nickel titanium and stainless steel wire were susceptible to corrosion. b) The nitride coating did not affect the corrosion of the alloy, but epoxy coating decreased corrosion. Titanium wires and epoxy-coated nickel titanium wires exhibited the least corrosive potential. c) For patients allergic to nickel, the use of titanium or epoxy-coated wires during orthodontic treatment is recommended.
6.	Platt *et al*[37]	2205 duplex stainless steel (Ni content: 4-6wt%) compared with 316L stainless steel (Ni content: 10-14%)	0.9% NaCl Solution Temp-37^0C,	2205 duplex stainless is an improved alternative to 316L for orthodontic bracket fabrication when used in conjunction with Ti, its alloys, or stainless steel archwires.

Sl. No.	References	Orthodontics wires	Medium, temperature, pH, period, method etc	Remark
7.	Rogers[38]	Stainless steel with silver soldered, gold plated, nickel plated; silver soldered, gold plated stainless steel; replated with gold after soldering.	Ringer solution, 0.1 M chloride solution; Deaerated Ringer's solution Temp-37^{0}C, pH 7	Electroplating with gold before and after silver soldering the stainless steel prevented crevice corrosion. The stainless steel surface was activated and prevented by the first layer of electrodeposited gold. The silver soldered alloyed with this gold layer so a second application of electrode-deposited gold was required to protect the joint from electrolytic action.
8.	Masahir *et al*[44]	Two common bracket alloys, stainless steels and Ti, and four common wire alloys, NiTi alloy, β-Ti alloy, stainless steel, and Co-Cr-Ni alloy,	0.9% NaCl Solution 3 days, Neutral pH.	a) SUS 304-NiTi and Ti-NiTi may remarkably accelerate the corrosion of NiTi alloy, which serves as the anode. b) The different anode-cathode area ratios used in this study had little effect on galvanic corrosion behavior.
9.	Wang *et al*[47]	NiTi wires	Artificial saliva, Room temperature, 30 days. Optical and scanning electron microscope (SEM)	a) Orthodontic NiTi wires were broken by stress corrosion cracking during service. b) The slight change in temperature will cause the dynamic phase transformation which causes the change in surface state. c) A tool-made notch in orthodontic NiTi wires can cause stress corrosion cracking.
10.	Chang *et al*[50]	Commercially pure titanium (CPT), Ti-6Al-4V (TAV), Ti-Ni (TN), Co-Cr-Mo alloy (CCM), 316L stainless steel (SSL), 17Cr-4Ni PH-type stainless steel (PH), and Ni-Cr alloy (NC).	Gamry corrosion test system, (1) sterilized Ringer's solution as a control for (2), (2) S. mutans mixed with sterilized Ringer's solution; (3) sterilized tryptic soy broth as a control for (4), and (4) byproducts of *S. mutans* mixed with sterilized tryptic soy broth.	a) *S. mutans* reduced the E_{OCP} of CPT, TAV, TN, and SSL, and the byproducts of *S. mutans* reduced the E_{OCP} of TAV, TN, SSL, and PH. b) *S. mutans* increased the I_{CORR} of pH, and byproducts of *S. mutans* increased the I_{CORR} of all the samples. c) *S. mutans* reduced the E_{CORR} of CPT, TAV and TN, and the byproducts of *S. mutans* reduced the E_{CORR} of TN, SSL, PH, and NC. d) *S. mutans* increased the I_{PASS} of CPT, and the byproducts of *S. mutans* increased the I_{PASS} of CPT, pH, and NC.

Sl. No.	References	Orthodontics wires	Medium, temperature, pH, period, method etc	Remark
11.	S.Maruthamuthu *et al*[51]	NiTi, Stainless steel round wire	Sterile as well as mixed bacteria inoculated artificial saliva. 12 hours, 37^0C. Potentiostat.	a) Bacteria slightly reduce the resistance and increase the corrosion current. b) NiTi-0.016 and SS-26 gauge were better candidate material for dental applications. c) Leaching of manganese, chromium, nickel and iron from the wires may be due to the availability of manganese oxidizers, iron oxidizers and heterotrophic bacteria in the saliva.
12.	Huang *et al*[53]	Ti-6Al-4V alloy	Artificial saliva with 0.5% NaF, with o.1%NaF+0.01-0.5% Bovine albumin (BA), 37^0C, pH-5, X-ray photoelectron spectroscopy.	a) The electrochemical mechanism of Ti-6Al-4V alloy in artificial saliva is related to the fluoride and bovine albumin concentration. b) Electrochemical impedance spectroscopy (EIS) is suitable for the study of the electrochemical behaviour of dental alloys.
13.	Schiff *et al*[55]	Three types of brackets (Co Cr, FeCrNi and Ti based brackets), corrosion resistance was compared with that of platinum	Three fluoride mouthwashes Fusayama Meyer artificial saliva used as reference solution	Bracket materials could be divided into two groups: Ti and FeCrNi in one and CoCr, which has properties close to those of Pt.
14.	Schiff *et al*[57]	Ti based wires – TMA, TiNb, NiTi, CuNiTi.	Three fluoride mouthwashes Fusayama Meyer artificial saliva used as reference solution (24 hour)	a) NiTi based alloys which were subjected to strong corrosion in presence of monoflourophosphate b) TMA corroded strongly with stannous fluoride mouthwash. c) TiNb was most resistant to corrosion.
15.	Huang[58]	Four different NITi commercial orthodontic archwires.	Fluoride mouthwashes , artificial saliva , commercial fluoride toothpaste or prophylactic gels 28-days.	a) The increase in surface roughness of NiTi orthodontic archwires in the commercial fluoride containing environments. b) Fluoride applications should be taken into account when considering the effectiveness of orthodontic appliances.

Sl. No.	References	Orthodontics wires	Medium, temperature, pH, period, method etc	Remark
16.	Kerosuo *et al*[67]	Different types simulated orthodontic appliances.	0.9% NaCl Solution	It showed significantly higher cumulative release of nickel under dynamic (simulated function) compared to static condition.
17.	Jose *et al*[70]	Nickel based alloys, One Noble alloy, One high noble alloy, & two copper aluminum alloys.	Artificial Saliva, 15 days, Metal casts were subjected to continuous flow of saliva thrice daily lasting 30 minutes each, consisting pH decreases and salinity increases.	a) Cu-Al alloys released Cu, Al, Ni, Mn & Fe. Ni-based alloys released Ni, Cr. b) Beryllium containing alloys released beryllium and Ni. c) Noble and High noble alloys were very resistant to corrosion. d) Ions released to be far below the tolerable upper intake levels for each ion.
18.	Manaranche *et al*[74]	Au, Pd, Ag, Cu, Zn, Ti. Precious alloys Pd-base, Au-Pt, Au-Pt-Pd, Au-Pd, Au-Ag-Cu alloys.	Electrochemical test; NaCl solution, 37^0C. pH – 7.4, Potentiometer, 2 h. Chemical corrosion ; 37^0C, Sodium chloride and lactic acid. pH-2.3, 7 days, ICP spectroscopy.	The Pd-base and Au-Pt-Pd dental alloys are the most resistant to chemical and electrochemical corrosion, even higher than gold.
19.	Cioffi *et al*[75]	NiTi wires	Flouridated artificial saliva, 37^0C, thin layer activation (TLA) 5% tensile strain.	a) Behaviour of NiTi alloy is highly affected by the fluoride content. b) TLA method in the biomedical field appears a suitable technique to monitor in real time the corrosion behaviour of medical devices.
20.	Zavanelli *et al*[76]	Pure titanium, titanium alloy (Ti-6Al-4V)	Air, synthetic saliva, Flouride+synthetic saliva. At room temperature. Scanning electron microscope.	Ti-6Al-4V alloy had highest value of fatigue; however there were no significant differences when compared with commercially pure titanium.
21.	Yukyo *et al*[77]	Dental magnetic attachment (ferric and austenitic stainless steel), Au-Ag-Pd alloy, type 4 gold alloys, Titanium.	0.9% NaCl Solution or 1% lactic acid solution at 37^0C. 7 days.	The contact of the stainless steel and the dental metals increased amount of ions released from the stainless steel. Corrosion resistance of type 316L is inferior to that of ferric stainless steel in contact with precious alloys.

Legend:

Fig. 1: Diagrammatic summary of the various types of corrosion