



Research article

In vitro wearing away of orthodontic brackets and wires in different conditions: A review



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ABSTRACT

Introduction: The release of metallic ions from orthodontic brackets and wires typically depends on their quality (chemical composition) and the medium to which they are exposed, e.g., acidic, alkaline, substances with a high fluoride concentration, etc. This review examines corrosion and wear of orthodontic brackets, wires, and arches exposed to different media, including: beverages (juices), mouthwashes and artificial saliva among others, and the possible health effects resulting from the release of metallic ions under various conditions.

Objective: This review aims to determine the exposure conditions that cause the most wear on orthodontic devices, as well as the possible health effects that can be caused by the release of metallic ions under various conditions.

Sources: A search was carried out in the Scopus database, for articles related to oral media that can corrode brackets and wires. The initial research resulted in 8,127 documents, after applying inclusion and exclusion criteria, 76 articles remained.

Conclusion: Stainless steel, which is commonly used in orthodontic devices, is the material that suffers the most wear. It was also found that acidic pH, alcohols, fluorides, and chlorides worsen orthodontic material corrosion. Further, nickel released from brackets and wires can cause allergic reactions and gingival overgrowth into patients.

1. Introduction

Orthodontic treatments are common to correct teeth and jaw position, for both aesthetic and health purposes. These treatments involve orthodontic brackets, archwires and wires, among others, and are in contact with the patient's oral cavity for the entire treatment duration, which can last for months or even years [1]. Orthodontic devices are thus exposed to long-term changes in pH, temperature, and different chemical substances; that can promote wear of devices and the release of ions from metallic materials [2]. Nickel-titanium alloys (NiTi) and stainless steel (SS) are commonly used materials in orthodontics; other materials are also used, such as titanium (Ti), β -titanium-molybdenum-zirconium-tin (TMA), copper-nickel-titanium (CuNiTi), iron-chrome-nickel (FeCrNi) and cobalt-chrome (CoCr) [3]. Ions from these alloys, particularly Ni, Fe and Cr, that are released into the oral cavity can produce various health issues [4]. Furthermore, as a result of corrosion and wear, orthodontic devices can undergo structural changes that alter the applied force, and subsequent involuntary movements of teeth [5].

2. Objective

This review examines “*in vitro*” studies that focus on corrosion of different brands of metallic brackets, arches, and wires and with diverse characteristics that are exposed to similar chemical conditions in the oral cavity, as well as, possible patient health complications caused by the release of metallic ions release.

3. Methods

A search was conducted in the Scopus database, for articles related to oral media that can corrode brackets and wires. The keywords used were “orthodontic wire” OR “orthodontic bracket” OR “orthodontic arc”. The initial search yielded 8 127 document results. After applying the first inclusion criteria “corrosion”, 660 results were returned, application of the second inclusion criteria was “ions” AND “release” resulted in 281 documents. From these, the exclusion criterion (“*in vivo*”) was used, which resulted in 113 documents. As the final step, a manual search was

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conducted to limit studies to those in which intra-oral conditions were simulated, such as a temperature of 37 ± 1 °C and the use of an artificial saliva medium, which resulted in 76 articles.

4. Brackets

In an orthodontic context, brackets are devices that are not replaced during the entire treatment, thus factors that can lead to their deterioration must be considered when they are used. Multiple “*in vitro*” studies have been conducted to determine the optimal materials for treatment and which specific conditions should be avoided. Most of these experiments were carried out at 37 ± 1 °C in artificial saliva. Table 1 summarizes these studies.

Nevertheless, few studies have focused on wire corrosion and the release of metal ions, although several analyses have been done on combined bracket-wire system. One study used SS brackets (brands 3M Uniket, Ormco and Tommy), and wires made of TMA (Ormco), NiTi (3M Unitek) and SS (Ormco), which were immersed in a prophylactic agent (acidified phosphate fluoride) to measure static and kinetic friction force levels. The results showed that systems that used TMA and NiTi wires had the highest level of corrosion [9], but high deterioration also occurred when wires and brackets made from materials with different compositions were used. Further, Schiff et al. examined the corrosion of FeCrNiMo (Ormodont), CoCrMoFe (Orthoplus), and TiAlV (Ormodont) brackets coupled with NiTi and CuNiTi wires in Elmex and Meridol brand mouthwashes; through scanning electronic microscopy (SEM), they found the FeCrNi bracket/NiTi wire system showed the most wear. Additionally, the release of Ni, Cr, and Fe ions was measured using inductively coupling plasma with mass detector (ICP-MS), an electrochemical analysis (measurement of corrosion potential and galvanic potential) indicated that the brackets acted as cathodes and wires and the wires as anodes within the oral cavity [3].

Different materials can be coated with other substances to avoid wear. Kang et al. coated SS brackets and wires (3M Unitek) with a diamond like carbon films approximately to 200 nm thick, and performed a frictional test to determine the friction coefficient between both implements (bracket-wire). The results showed that coating the wire decreased the friction coefficient [22], indicating reduced orthodontic device corrosion. Furthermore, titanium nitride's (NTi) capacity to prevent corrosion of SS brackets was examined using polarization curves, which aid in the analysis of corrosion potential. It was found that a single layer of NTi on SS brackets (Ormco, Tommy, 3M Unitek and Dentarum) exposed to artificial saliva did not produce an anti-corrosive effect [10, 23]. On the other hand, Liu et al. confirmed that coating NiTi brackets with multiple layers of NTi increased corrosion resistance; corrosion potential was reduced by one order of magnitude [11].

Deterioration can also be caused by dental hygiene products. Dental hygiene products that contain fluoride help prevent tooth decay but could corrode brackets with an exposure of more than 18 months [12]. In this regard, Khoury et al. determined a suitable rinse to remove residue after fluoride application, that would reduce corrosion risk [13]. Other research on mouthwash has indicated that stannous fluoride (the active ingredient in some mouthwashes) produces the highest level of ions release for FeCrNi brackets [14], while fluoride-containing Olafur causes the most wear on devices made of CuNiTi, therefore, it is recommended to avoid these combinations of brackets and mouthwash. For the specific case of FeCrNi brackets from Ormodont, when the material was immersed in Meridol mouthwash, a respective release of 14,800 and 1,060 $\mu\text{L g}^{-1}$ of Ni and Cr, occurred, which corresponded to were the highest concentrations of ions released [14]. This concentration of Ni exceeds the recommended daily intake for humans, and could therefore cause adverse health effects. The health effects of released ions are discussed in more detail in Section 4.

In addition to hygiene products, the oral cavity is constantly exposed to food compounds that can cause serious damage to orthodontic devices, specifically food with an acidic pH. Various studies have explored the

effect of different types of beverages on orthodontic device deterioration by analyzing to their pH levels. The results of gravimetric and current density analysis have indicated that acidic beverages produce greater wear on brackets, particularly orange juice [16] and Coca Cola, the latter of which led to a 4% weight loss over six weeks [15].

Furthermore, prominent studies have been conducted regarding risk assessment when using recycled brackets which allows patients to save money on treatment [24]. Most studies have determined there is no significant difference in the corrosion of new and used brackets [18, 25, 26], which they confirmed by analysing the release of Cr ions using ICP and AAS.

Material biocompatibility must also be considered to prevent damage at the cell level. For example, to determine the biocompatibility of SS brackets, Prasetyady et al., performed cytotoxicity tests and verified that this material had as high percentages of viable cells; that is, SS did not produce irreversible damage to cells at short exposure times [19].

5. Orthodontic wires and archwires

In addition to brackets, orthodontic wires and archwires are also susceptible to deterioration. To determine the corrosion resistance of orthodontic wires, studies have analyzed wires made of various materials because there is no ideal wire that can be used for the entire treatment period; these are regularly replaced [27]. Table 2 details the most relevant studies on corrosion of orthodontic wires and archwires made from different materials and immersed in diverse media. In orthodontics, the most commonly used wires are made of SS and NiTi alloys [28]; however, other alloys such as TMA, CuNiTi, titanium-niobium (TiNb) [29] and nickel-titanium-cobalt (NiTiCo) [30].

Wires made from NiTi alloy are considered the best biomaterials due to their shape memory effect, super elasticity and good biocompatibility [28]. However, Ni can cause adverse effects in some individuals. Arciniegas et al. characterized a new Ni-free material made of Ti, Zr and Nb, and determined this new material had a higher corrosion potential, that is less susceptible to corrosion in comparison to NiTi commercial wires (Dentarum, Forestadent, Ormco, GAC, 3M Unitek). Additionally, this new material had good biocompatibility [62].

As with brackets, the environment in the oral cavity directly affects wire corrosion. For example, several studies have analyzed the influence of fluorides and chlorides; separately, these can cause serious damage to orthodontic materials [31, 32], while together, they can lead to even more damage, as they can produce pitting corrosion visible in SEM micrographs [28]. Additionally, both acidic pH [33] and alcohol media can promote the corrosion process [34, 35].

To avoid oral diseases such as bacterial plaque and cavities, mouthwash is commonly used. These normally, have various compounds that do not affect the oral cavity, but they can cause deterioration of orthodontic devices [34]. For example, Jamilian et al. analyzed the release of Ni and Cr ions for one week for NiTi and SS wires (American Orthodontics) in artificial saliva and two mouthwashes, Oral B and Orthokin. ICP measurements indicated that NiTi wires released fewer Ni and Cr ions with Orthokin while SS released fewer with Oral B [36]. They also found that dental restoratives, regardless of fluoride content, had a low effect on wire wear.

Patients' diet is another important fact in orthodontic device corrosion. Sherief and Abbas examined the behaviour of SS, NiTi and TMA wires (Ormco) exposed to heptane, citric acid, and ethanol by simulating fatty foods, citrus fruits, and alcoholic drinks, respectively. They concluded that of the analyzed materials SS had the highest corrosion activity and of the media, citric acid caused the most deterioration, which was determined by observing an increase in current corrosion and a decrease in potential corrosion [35]. Conversely, Erwanyah and Susilowati analyzed the effect of *Salacca zalacca* fruit extract on SS wires and found a corrosion inhibition effect with 300 ppm of fruit extract in artificial saliva as they observed that less Ni was released from the wire with this treatment [38].

Table 1. Main studies on corrosion of orthodontic brackets in different environments.

Device	Material	Brand	Released ions	Study media	Exposure time	Analysis method	Ref.
Brackets Wires	Fe–Cr–Ni–Mo Co–Cr–Mo–Fe Ti–Al–V Ni–Ti Cu–Ni–Ti	Ormodent Ortho Plus Ormodent Ormodent Ormodent	Cr Ni Fe	Artificial saliva Elmex® mouthwash Meridol® mouthwash	2 months	ICP-MS SEM Polarization curves	[3]
Brackets Wires	SS NiTi SS	3 M Unitek	-	Tooth paste	12 h	Friction test SEM	[6]
Brackets	SS	3 M Unitek Forestadent MEM Dental Technology	-	Artificial saliva pH 4.9 pH 7.8	1 day 7 days 28 days	ICP MS	[7]
Brackets	SS	Libral Traders	-	Artificial saliva Sodium chloride Pepper Turmeric	24 h	Optical microscopy	[8]
Brackets Wires	SS SS Ni Ti	DynaLock Tomy Ormco 3M Unitek Ormco	-	Artificial saliva Hydrofluoric acid Acid phosphate fluoride	24 h	Friction force	[9]
Brackets Wires	Coated Ni–Ti Un coated SS	Tommy Co. 3M Unitek	-	Artificial saliva Acid phosphate fluoride	100 min	Constant current corrosion Corrosion at constant potential	[10]
Brackets	Coated Ni–Ti Un coated	-	-	Artificial saliva	16 h	SEM XRD Polarization curves EIS	[11]
Brackets	Ti–Al–V	Ormco	-	Fluoride gel Mouthwash	6 months 12 months 18 months 24 months	Gravimetry SEM	[12]
Brackets	Ti–Al–V	-	-	Fluoride gel	2 min 4 min 12 min	SEM Gravimetry	[13]
Brackets	Fe–Cr–Ni–Mo Co–Cr–Mo–Fe Ti–Al–V	Ormodent Ortho Plus Ormodent	Co Cr Ni Ti	Artificial saliva Elmex® mouthwash Meridol® mouthwash Acorea® mouthwash	24 h	SEM Polarization curves ICP-MS	[14]
Brackets	SS Ni–Ti	Dentaurum	-	Artificial saliva Coca-Cola Lemon juice Vinegar	3 weeks	Gravimetry	[15]
Brackets	SS	Dentaurum	-	Artificial saliva Apple juice Orange juice Coca-Cola	5 min	Current measurement	[16]
Brackets Wires League	SS	-	Ni	pH 4.2 pH 6.5 pH 7.6	1 h	AAS	[17]
Brackets	SS Ni-free	Victory Sprint	Cr	Artificial saliva Solution pH 4.2 Solution pH 6.5 Solution pH 7.6	0.25 h 1 h 24 h 48 h 120 h	ICP-AES	[18]
Brackets	SS	Gemini® Synergy®	Ni Cr	Artificial saliva	16 days 28 days 35 days	EDS ICP Cytotoxicity	[19]
Brackets	SS	Tomy Inc Dentaurum	Fe Cr Ni Mn	Sodium fluoride Acetic acid pH 3.5 and 6	3 days	SEM Spectrometry UV-VIS ICP-OES Selective fluoride electrode	[20]

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Table 1 (continued)

Device	Material	Brand	Released ions	Study media	Exposure time	Analysis method	Ref.
Brackets	SS	American Orthodontics Dentaurum	Cr	Artificial saliva	1 day	SEM EDX ICP	[21]
			Co		7 days		
			Cu		28 days		
			Ni				
			Fe				

Due to their cytotoxic effects, Ni and Cr ions released from orthodontic wires are of greatest interest [33]. However, the release of Ti has also been focused on due to biocompatibility and its anticorrosive capacity [39]. According to some studies, more Ni is released than Cr in certain media such as artificial saliva, acidic media, and media with fluorides [33, 36, 38]. On the contrary, small amounts of Ti are only released when acidic media is used [33, 34, 39], which demonstrates it has a high potential to inhibit corrosion.

Some studies have addressed the possibility of coating wires to prevent its corrosion; however, the effect of coating depends on the environment to which the material is exposed. For example, coating NiTi wires with diamond-like carbon (DLC) and then exposing them to Phos-Flur mouthwash reduced the release of ions by 93% [40]. Another study found that corrosion could be reduced by up to 85% for NiTi wires coated with polyamides in an artificial saliva medium without affecting their elastic properties or the force required to achieve teeth movement [41]. When comparing uncoated NiTi wires and those coated with Ti and rhodium nitride in artificial saliva media exposed to various mouthwashes (Listerine, Curasept ADS[®] and Gengigel), researchers found that the rhodium-coated wires showed better anticorrosive capacity in all media [34]. Likewise, Chang and Yen studied the effect of coating NiTi wires with a ZrO₂ film, and found that this coating reduced the release of Ni in artificial saliva by 75% [42]. Similarly, Anuradha et al. tested a Ti sputtered coating that completely inhibited Ni release in NiTi wires [43], and Katić et al. determined that corrosion resistance of nitride-coated and uncoated NiTi wires decreased in media with a high fluoride content, while rhodium-coated wire was more resistant in media with low fluoride content [44]. Additionally, Nahusona and Koriston demonstrated watermelon rind extract's ability to inhibit corrosion up to 46% despite not being a coating as such [45].

In terms of materials, TMA and TiNb wires are better at resisting fluoride wear compared to NiTi and CuNiTi wires [46], while SS wires have the lowest resistance to corrosion in comparison to those made of NiTi or TMA [35]. NiTi alloys that include copper in their composition are susceptible to deterioration than those without copper [48], while those that include cobalt have a similar wear to those made of NiTi [30].

In another study, Oh et al. proposed a "super material" made from SS, which was compared to four brands of commercial wires; the proposed material had greater resistance to localized corrosion [55].

Another variable that directly influences corrosion is wires thickness, which is important to consider because different types of wires are used for each stage of orthodontic treatment. Kao et al. examined SS and NiTi wires (3M Unitek) with thicknesses of 0.014 in (SS and NiTi) and 0.016 in (NiTi) that were exposed to artificial saliva at different pH values. They found the thinner wires were more susceptible to corrosion [33].

Among the brands analyzed, Rematitan showed the highest release of Ni and Ti from NiTi wires exposed to artificial saliva with respective values of 0.264 and 0.374 mg □ L⁻¹ [42]. When comparing studies on the release of Cr from NiTi wires exposed to media with a high fluoride content, it was determined that the American Orthodontics brand was the least resistant, releasing of 53.6 μg □ L⁻¹ [36], which is approximately 10% greater than values obtained in other studies [33, 38]. However, according to these results, the wires released a lower concentration of metals than the daily-recommended intake.

As mentioned, biocompatibility is a critical factor in medical and orthodontic treatment. Over time, materials are modified to either

improve the treatment or achieve a better appearance, which may affect biocompatibility. Rongo et al. compared the biocompatibility of wires coated with various aesthetic materials versus conventional metal wires and determined that the use of aesthetic wires did not affect biocompatibility [63].

6. Orthodontic bands and tubes

Unlike brackets and archwires, orthodontic bands and tubes have not been extensively studied. However, the cytotoxic effect in cell cultures has been explored. For example, SS bands (Ni, Cr, Mo, and Fe) with no soldering, silver soldering and laser-soldering were exposed to *Saccharomyces cerevisiae* cells for two days at 37 °C. Each group allowed a respective average of 45%, 30% and 70% of viable cells to grow compared to the number of cells that grew with no band exposure [64]. On the other hand, another study evaluated the cytotoxic effect of bands (Ni, Cr, Mo, and Fe) with no soldering and silver soldering for 24 h at 37 °C, and determined that neither groups showed cytotoxic reactivity to L929 cells [65]. Additionally, Ormco, R.M.O., Dentarum and G.A.C. bands were studied with fibroblast L292 cells at exposure of 3 and 14 days; results indicated that no band had a cytotoxic response [66].

7. Health effects of released ions

Ni and Cr ions are known to cause allergic reactions in approximately 10% of the population [62]; these ions are also associated with toxic and carcinogenic effects [67]. Nevertheless, NiTi alloys are the most commonly used materials in orthodontic treatments [41].

In the majority of studied cases, the amount of ions released did not exceed the acceptable daily intake (Ni: 200–300 μg; Cr: 50–200 μg), which indicates that few patients will suffer toxic and/or carcinogenic effects although some allergic reactions may occur [68]. Some patients may experience skin rashes, swelling and painful erythematous lesions on oral and labial mucosa [67]. Further, Pazzini et al. demonstrated that Ni can affect the periodontal status of allergic patients because it can cause an increase in gingival index scores [69]. Gursoy et al. determined that the continuous release of low doses of Ni can promote the growth of epithelial cells, which can cause gingival overgrowth [70].

8. Analytical methods to measure wear

Most studies used the following procedure to determine the level of corrosion of orthodontic brackets, wires, and arches. First, the materials are disinfected, rinsed and dried, after which they are immersed in a specific medium, such as artificial saliva, mouthwashes, acids, beverages, fluorides, or chlorides, and then maintained at a temperature of 37 °C throughout the analysis.

Various analysis techniques have been used to measure deterioration of orthodontic brackets (Tables 1 and 2). Among them are, gravimetric analysis to measure weight loss [15], and atomic absorption spectrometry-AAS [17] and ICP to measure the release of Ni and Cr [18]. In addition, other analysis have been carried out for the structural characterization of material, including the measurement of friction forces [9], SEM to examine microscopic-level pitting [14], and X-ray diffraction-XDR to analyze the formation of characteristic oxides or wire

Table 2. Main studies on corrosion of orthodontic wires and arches in different environments.

Material	Brand	Released ions	Study media	Exposure time	Analysis method	Ref.
Ni-Ti SS	Dentaurum Tiger Ortho		Artificial saliva Nitric acid		SEM AAS Polarization curves	[28]
TMA TiNb NiTi CuNiTi			Artificial saliva Elmex® Meridol® Acorea®		Polarization curves SEM	[29]
Ni-Ti Ni-Ti-Co			Artificial saliva pH 2.4 Artificial saliva pH 5.3 Artificial saliva pH 6.2	30 min	XPS ICO-OES Polarization curves	[30]
Ni-Ti	Fort Wayne Metals Research Products Corporation	Ni	NaCl 0.9%	24 h 48 h 72 h 0.5 month 1 month 2 months 4 months	AES SEM ICP Polarization curves	[31]
Ti-Ni	ORMCO RMO Dentaurum Shin-Ya Co		Artificial saliva Fluoride-free mouthwash Fluoride mouthwash Toothpaste Fluoride gel	28 dyes	AFM	[32]
SS Ni-Ti		Ni Ti Cr	Artificial saliva + NaF Artificial saliva pH 4 Artificial saliva pH 6.5	48 weeks	AAS	[33]
Coated and un coated Ni-Ti	Dentsply GAC	Ni Ti	Artificial saliva Listerine Curasept ADS® 205 Gengigel	28 dyes	ICP	[34]
SS TMA Ni-Ti	Ormco		Heptane Citric acid Ethanol	28 days	Polarization curves Friction forces	[35]
Ni-Ti SS	American Orthodontics	Ni Cr	Artificial saliva Oral B Orthokin	1 h 6 h 24 h 7 days	ICP-AES	[36]
Ni-Ti Cu-Ni-Ti	Ormco GAC 3 M		Dental restoratives	24 h 10 days	SEM Microhardness measurement Selective fluorine electrode	[37]
SS		Ni Cr	Artificial saliva Salacca zalacca extract	24 h	AAS	[38]
Ni-Ti	Ormco Orthonol Kuo-Hua Co. Shin-Ya Co.	Ni Ti	Artificial saliva at pH 2.5 Artificial saliva at pH 3.75 Artificial saliva at pH 5.0 Artificial saliva at pH 6.25	1 day 3 days 7 days 14 days 28 days	AAS SEM Rugosity	[39]
Coated and un coated Ni-Ti	Grikin Advanced Materials		Phos-Flur mouthwash	12 weeks	SEM Friction force	[40]
Coated and un coated Ni-Ti		Ni	Artificial saliva	30 days	Rugosity Tensile forces Friction force Corrosion tests AAS	[41]
Coated and un coated Ni-Ti	Rematitan®	Ni Ti	Artificial saliva	3 h	SEM Polarization curves ICP-AES	[42]

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Table 2 (continued)

Material	Brand	Released ions	Study media	Exposure time	Analysis method	Ref.
Coated and un coated Ni-Ti	3M Unitek	Ni Ti	Artificial saliva	30 days	SEM ICP	[43]
Coated and un coated Ni-Ti			Artificial saliva Elmex Mirafluor MI Paste	28 days	EIS	[44]
SS			Artificial saliva Watermelon rind extract		Polarization curves	[45]
Ni-Ti Cu-Ni-Ti TMA Ti-Nb	Ormco		Artificial saliva NaF	1 h	XPS SEM Polarization curves	[46]
Ni-Ti	Memory-Metalle GAC	Ni	Phosphate buffer solution + NaF	6 days	Thin film activation	[47]
Ni-Ti Cu-Ni-Ti	3M Unitek Neosentalloy-GAC ORMCO	Ni	Artificial saliva	1, 3, 5, 10, 24, 120, 168, 360 y 560 h	ICP-MS Polarization curves	[48]
SS (Ni free) SS (Containing Ni)	Scheu-Dental	-	Artificial saliva pH 2.5, 3.5, 4.5, 5.5 and 6.5	-	SEM Open circuit potential Potentiodynamic polarization curves	[49]
SS NiCr	-	-	Artificial saliva Powdered juice	-	Potenciodynamic polarization study Alternating current impedance spectra	[50]
SS NiTi	Dentsply GAC	-	Artificial saliva Probiotic bacteria <i>Lactobacillus reuteri</i>	28 days	Electrochemical impedance spectroscopy	[51]
SS NiTi	-	-	Acidic artificial saliva		Cyclic potentiodynamic Potentiostatic tests X-ray photoelectron AFM	[52]
SS	-	-	Artificial saliva Roseday 5M	-	Potentiodynamic polarization study AC impedance measurements	[53]
SS Rhodium coated SS	Dentsply GAC International	-	Artificial saliva and mouthwash (0.05% NaF)	3 h	AFM SEM	[54]
SS	Dentaurum 3M Unitek G&H Ormco	Ni	Artificial saliva	12 weeks	SEM Polarization curves XRD AAS	[55]
SS	-	-	Artificial saliva Juice with Digene tablets	-	Linear polarization resistance	[56]
SS	-	Fe	Acidic drinks	3.5 h	AAS	[57]
SS	-	Fe Cr Ni	Lactic acid	7 days	IPC	[58]
Ni-Ti	Shenzhen Superline Technology		NaF NaCl	1 h	SEM Corrosion potential Potentiodynamic polarization Cyclic potentiodynamic polarization	[59]
Ni-Ti	ORMCO RMO Dentaurum Shin-Ya Co		Artificial saliva + NaF	2 h	AFM Polarization curves	[60]
Ni-Ti	American Orthodontics		Artificial saliva		SEM Polarization curves	[61]

corrosion [11]. Finally, electrochemical techniques have also been used such as polarization curves [3], corrosion at a constant current and potential [10], and electrochemical impedance spectroscopy-EIS [11], to determine materials' resistance to corrosion.

The analyses focused on characterizing orthodontic wires and arches are similar to those done with brackets, with some additional techniques,

such as X-ray photoelectron spectroscopy, XPS [46], atomic force microscopy, AFM [32], and thin layer activation [47]. Gioffi et al. performed an analysis under stress conditions and found no influence of stress on Ni release [47].

Cytotoxic effects have been determined by exposing cultured cells "in vitro" to different concentrations of Ni and Cr [70] and to extracts with

liberated metallic ions [63]. To analyze the toxic effects of Ni on gingival overgrowth, epithelial cells cultured in Dulbecco's Modified Eagle's Medium (DMEM) [70] have been used. Regarding biocompatibility, human osteosarcoma cells have been cultured, and artificial saliva extracts with various concentrations of fluorides added [33, 71]. Some studies have also been carried out with human gingival fibroblasts, which are cells native to the oral cavity, extracts of DMEM with ions released from orthodontic wires were added to these cells [63] and viable cells were analyzed.

9. Discussion

According to the studies reviewed in this article, brackets quality is closely related to the brand and chemical composition of the brackets materials. This suggests that better-quality material capable of withstanding severe changes in oral conditions, such as chemical changes, e.g., pH (acid and alkaline), and fluorides or chlorides contents, needs to be developed.

In general, orthodontic devices with the most corrosion are made of SS, and exposure time also plays an important role. Therefore, the fact that brackets stay in the mouth much longer than wires (i.e., brackets are placed for the entire orthodontic treatment, while orthodontic wires and arches are replaced approximately every 30 days, depending on treatment requirements) needs to be taken into account. During actual treatment, devices are subjected to various conditions; therefore, it is necessary to address the corrosion of orthodontic materials at the “*in vivo*” or “*in situ*” level, the oral cavity regularly encounters factors that cannot be replicated in “*in vitro*” studies. Additionally, orthodontic materials must withstand very strong mechanical stress, either to move the teeth or jaw or due to friction between brackets and orthodontic wires [72].

Therefore, we face two dilemmas, one related the bracket material and the other the type of mouthwash. Several studies have evaluated the possibility of coating the orthodontic material to avoid corrosion, however, before considering this option, the conditions to which the oral cavity will be exposed must be analyzed. For example, instead of coating the wire to avoid wear caused by fluorides, a suitable mouthwash can be used [3, 14, 34, 36]. Considering that for different materials one mouthwash can be more corrosive than another, certain conditions should be avoided or reduced during orthodontic treatments such as acidic pH (fruits and citrus drinks, Coca Cola) and the presence of ethanol (alcoholic beverages and some mouthwashes), fluorides and chlorides. On the other hand, it is important to mention that few corrosion studies have been conducted with foods and drinks common in people's diets. In the case of fluoride rinses, damage could be prevented with an appropriate water rinse; for example, an optimal concentration of *Salacca zalacca* to inhibit deterioration of orthodontic materials was determined, but the amount of fruit corresponding to that concentration has not been indicated [38].

Additionally, Ni and Cr have possible adverse effects on human health and are therefore particularly focused on relevant research. In general, the release of ions from orthodontic materials does not exceed the recommended daily intake, meaning that in the short-term, health effects will not occur.

However, under specific corrosion conditions, such as those studied by Schiff et al. [14], some medical complications may arise. Short-term effects, like skin rashes, swelling, and erythematous lesions on oral mucosa could occur and gingival index scores may increase.

In contrast, Ti is not of medical interest but it is very important regarding developing new materials because of the low release of Ti ions from Ti-based materials [39]. Coatings using this metal have been analyzed in context of reducing corrosion of orthodontics devices, with results showing that the coating decreased the release of Ni [73].

Finally, in addition to brackets, wires and arches, other orthodontic materials are less frequently used but still susceptible to corrosion such as crowns, bands, denture bases and space maintainers [74].

10. Conclusions

The studies analyzed in this review are very heterogeneous, however, they still provide a general overview of corrosion of metal orthodontic devices. Among the most notable observations is that SS materials are the most prone to corrosion, while those made from Ti are the most resistant. Further, certain mouthwash brands can degrade materials, and so dentists must recommend products that are compatible with the orthodontic material used in the treatment. Specifically, acidic conditions must be avoided, and an adequate rinse must be ensured in the case of fluoride use. Furthermore, coating materials could be an efficient anticorrosive method in some environments, but could produce the opposite effect in others. Finally, Ni and Cr can cause adverse health effects; however, Cr is released in lower amounts than Ni, but in most cases none of the released metals exceed the recommended daily intake. Nevertheless, allergic reactions and gingival overgrowth can occur.

Declarations

Author contribution statement

Patricio J. Espinoza-Montero: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Marjorie Montero-Jiménez: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Lenys Fernández, Jose Luis Paz, Sandra Macías Ceballos: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

José Luis Piñeiros: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Additional information

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