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Nickel release from orthodontic retention wires—The action of mechanical loading and pH

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ABSTRACT

Nickel (Ni) is a potent sensitizer and may induce innate and adaptive immune responses. Ni is an important component of orthodontic appliances (8–50 wt%). Due to chemical and mechanical factors in the oral environment, Ni is released from these appliances. Retention wires are in situ for a long period of time.

Objectives. To quantitatively evaluate the influence of mechanical loading and pH on the nickel release from orthodontic retention wires.

Methods. Five different types of multi-stranded wires (Original Wildcat, Noninium, Lingual retainer, Dentaflex 3-s, Dentaflex 6-s), were submersed for 24 h in either 10 ml of distilled water or lactic acid, both submitted to cyclic loading in a 3-point bending test (0×, 1000×, 10,000×). The solutions were analyzed by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS), and the data was statistically analyzed (ANOVA, $p < 0.05$).

Results. Mechanical loading has a strong effect on the Ni release from orthodontic retention wires, especially in distilled water. Acidity has more impact on Ni release when compared to mechanical loading. Manganese-steel “Ni-free” wires released quantifiable amounts of Ni due to trace elements of Ni within the wire.

Significance. All investigated wires release considerable amounts of Ni to which exposure may have biological implications.

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1. Introduction

Nickel (Ni) is the most common cause of allergic contact dermatitis, with an estimation of incidence up to 17% in women and 3% in men [1]. The difference in Ni allergy incidence between male and female is related to daily contact to jewelry and especially (ear) piercings in the female population, and is considered the most important cause of Ni sensitization [2–4]. Nevertheless, other important sources of exposure are cosmetics, detergents, coins, the professional environment, and dentistry [5–7].

In dentistry, nickel is used in a broad spectrum of applications, but mainly in orthodontics for arch wires, bands, headgear, and brackets. During active orthodontic treatment, those appliances are used for a relatively short period of time with an average of approximately 2 years. Many studies report on the release of nickel from these fixed orthodontic appliances in both static and dynamic conditions [8–10]. To achieve teeth position stability and prevent immediate relapse after the active orthodontic treatment it is common practice to apply a retainer wire. These wires remain in the oral cavity for many years or even decades [11]. The most commonly used wires are made of stainless steel containing

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Table 1 – Brand, composition (wt%) of the wires by EDAX analysis, dimensions and surface area (A_w) of the wires used in the study. Other relevant data are: r_{wire} radius of the wire, r_{int} radius of the circular space in the center of the strand; n number of turns of the strand; N number of strands of each wire, and the calculated length of strand L_s . L_{wire} is the length of the wire and was in all experiments 22.0 mm.

Wire	Ni	Fe	Cr	Mn	d	A_w	r_{wire}	r_{int}	n	N	L_s
Noninium ^{a,d}	0.0	57.4	23.1	19.5	0.45	46.0	0.105	0.015	9.5	3	23.1
Original Wildcat ^{b,e}	8.9	69.7	19.5	1.2	0.45	46.6	0.105	0.015	10.6	3	23.4
Lingual retainer ^{c,e}	8.0	70.4	19.8	1.2	0.81	84.8	0.188	0.027	6.6	3	23.7
Dentaflex 3-s ^{a,e}	8.6	72.0	17.9	1.0	0.45	48.0	0.105	0.015	13.2	3	24.1
Dentaflex 6-s ^{a,e}	8.8	69.7	19.6	1.3	0.45	69.8	0.065	0.095	16.7	5 + 1	27.7

^a Dentaureum, Ispringen, Germany.

^b Dentsply International, USA.

^c Unitek 3M, Monrovia, USA.

^d Ni trace elements of <0.2% can be included according the manufacturer.

^e Contain also traces of Cu (~0.3 wt%) and Co (~0.3 wt%).

approximately 8 wt% nickel. Nowadays, these wires are multi-stranded instead of plain round or rectangular wires. In this way, they can achieve increased mechanical retention and improved physiologic movement of the teeth. The cross section of a strand can be round or rectangular and a wire is formed from three to six fine strands [12]. Little attention is paid to adverse effects on dental or periodontal health after placement and if it is mentioned it is mostly related to the oral hygiene [11,13]. To our knowledge reports on metal release, or specific the nickel release, from orthodontic retainer wires are scarce. One case report shows the clinical relevance of these retainer wires in a Ni allergic patient [14]. The most important factor influencing Ni release from orthodontic appliances is corrosion, i.e., deterioration of a (dental) material with metallic ion release. One case study reports clinical signs of corrosion from a solder joint of a removable retainer containing Ni. However, the causative agent of the reaction is not reported [15].

The oral environment is dynamic, where factors like pH variation, temperature, salivary conditions, mechanical load, microbiological and enzymatic activity/bacterial acidic production have effect on the corrosion rates of metals [2,16,17]. As mentioned above, retainer wires are twisted multi-strands and the Ni release rate of these wires might in principle be different compared to straight, plain wires, especially when subjected to movement induced by teeth function and para-functional habits. Furthermore, plaque is frequently accumulated on the retainer wires [13]. This can locally lower the pH and subsequently enhance Ni release.

The aim of this study was to report on the nickel release of orthodontic retention wires which are subjected to mechanical loading at different pH. The Ni release of the wires was measured under standardized in vitro conditions. Furthermore, different types of wires were investigated, i.e., triple or six-stranded, with different diameters and different chemical composition.

2. Materials and methods

The type and brand of 4 stainless steel and 1 “nickel-free” retention wires investigated in this study are shown in Table 1. The multi-stranded wires were sectioned in specimen of

22.0 mm in length. Three hundred and sixty specimens of the 5 different types of wires were divided into two main groups: (1) wires submersed in distilled water and (2) wires submersed in lactic acid 90%. Each main group was further divided into three subgroups with (A) wires not exposed to cyclic loading; (B) wires exposed to 1000 cyclic loading cycles; (C) wires exposed to 10,000 cyclic loading cycles. Each subgroup consisted of 12 wires.

For the cyclic loading, a metal-free setup was used where the wires were exposed to a three-point bending test. The test setup consisted of a modified injection syringe (Terumo® Syringe, Luer Lock Tip, 10 ml) in which two parallel holes were made in each side of the syringe. Two wires per syringe were placed in the holes and were loaded by an air driven piston with a frequency of 1 Hz and a loading cycle of 50%. Movement of the piston of the syringe led to a bending force in the wires, with a deflection of 2–3 mm. Before testing, the specimens were ultrasonically cleansed with ethanol during 1 min, rinsed with distilled water and dried. The syringe with the 2 wires was placed in a plastic vial filled with 10 ml of distilled water or the lactic acid solution (ISO standard 10271: pH = 2.3, [NaCl] = 5.83 g, [Lactic acid] = 9 g/l) and mechanically loaded. After 24 h the wires were removed from the solution and 1 ml of nitric acid 6.5% was added to each sample, for measurement purposes.

The solutions were analyzed by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) (ELAN 6100, SCIEX – Toronto, Canada) to quantify the amount of ions released. The ICP-MS was calibrated against standard solutions consisting of 1% nitric acid and two solutions of Ni, Cr, Co, Fe, Mn and Cu ions in a concentration of 100 ppb and 10 ppb. Control samples were also analyzed and the values for each ion were subtracted from each analyzed sample. These controls were the experimental media (i.e., distilled water or lactic acid) without contact with the specimens. The composition of the wires was evaluated by Scanning Electron Microscopy-Energy-Dispersive X-ray spectrometry (SEM-EDAX) (model XL20, FEI Company, Netherlands), which has a detection limit of 0.2 wt%.

For the calculation of the surface area of each specimen a few formulas were used. The length of each strand of a helix shaped wire can be calculated according to Eq. (1), where L_s is the length of the strand, L_{wire} the length of the wire, and n is the number of turns of the strand. The radius of the circular

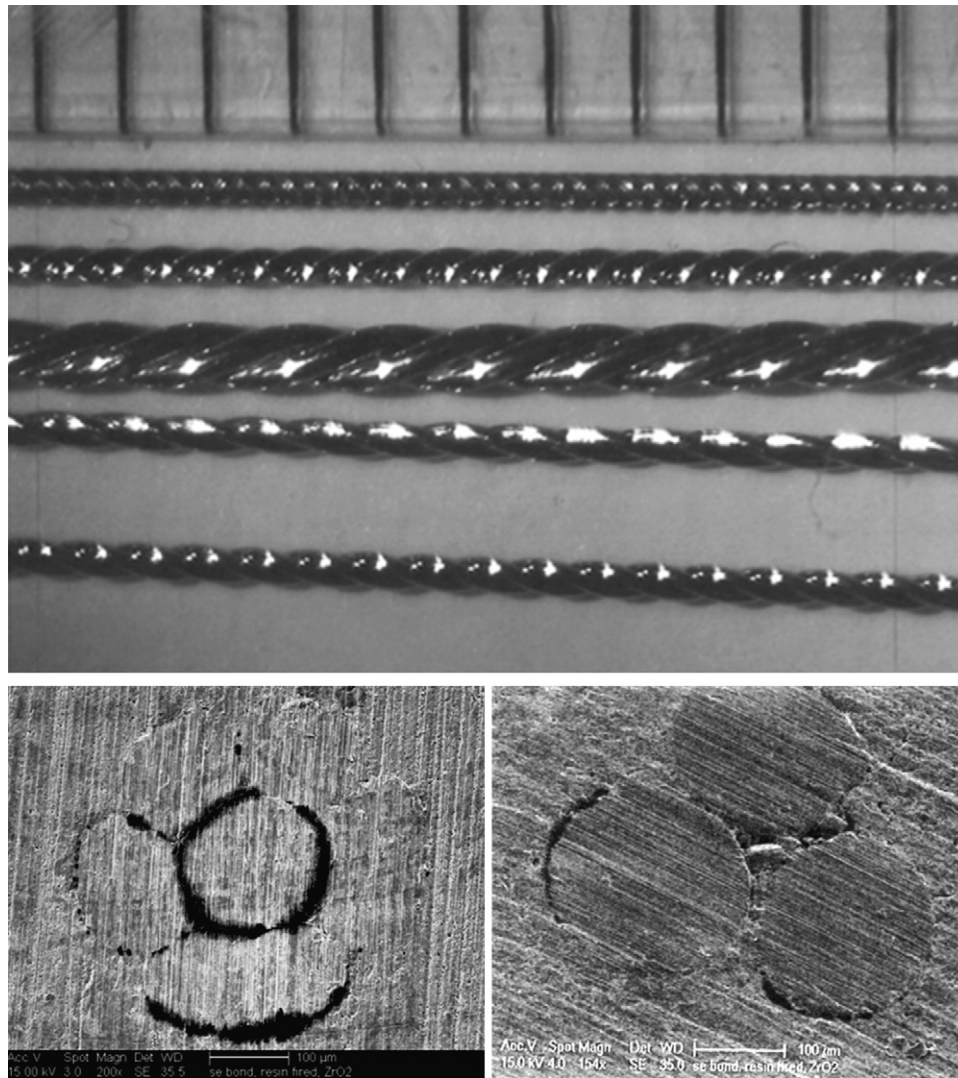


Fig. 1 – Macroscopic photograph of the five wires used in the study (10×) (top); SEM photograph of the structure of the Dentaflex 6-s (150×) (bottom left) and Original Wildcat wire (200×) (bottom right).

space in the center of the strand is given by the r_{int} and the radius of the wire by r_{wire} .

$$L_s = \sqrt{((2\pi n(r_{int} + r_{wire}))^2 + L_{wire}^2)} \quad (1)$$

The area of the wire can be calculated according to Eq. (2) and for the Dentaflex 6-s wire, with 5 strands turned around one central strand, Eq. (3) is used.

$$A_w = 2N\pi r_{wire}^2 + 2N\pi r_{wire}L_s \quad (2)$$

$$A_w = 2N\pi r_{wire}^2 + 2N\pi r_{wire}L_s + 2\pi r_{int}L_{wire} \quad (3)$$

The results of the nickel release were statistically analyzed using two and three-way ANOVA. For the two-way ANOVA the post hoc analysis was performed with the Tukey test at a p -level of 0.05. The software used was SigmaStat 3.1 (SYSTAT Software, Inc., Point Richmond, CA, USA). It should be noted that all data, experimental and literature, are converted

to $\mu\text{gcm}^{-2}\text{week}^{-1}$, using the given experiment conditions (volume of the medium, specimen surface area, observation period).

3. Results

Fig. 1 shows the 5 different wires investigated in this study. All are classified as triple or six-stranded, round, twisted orthodontic retainers although the specimens showed a quite different appearance. A cross section of the Dentaflex 6-s and the Original Wildcat wire observed with the scanning electron microscope are shown in Fig. 1. While 3-stranded wires consisted in three strands twisted around a void, the 6-stranded wire was constituted by five strands twisted around one central strand. The specific dimensions and the calculated surface area, according to Eqs. (1)–(3), of each wire are summarized in Table 1.

The composition, in weight percentage (wt%), of the wires was analyzed by SEM-EDAX and is shown in Table 1. The

Table 2 – Ni release (ppb) from one “Ni-free” and four stainless steel twisted, round, orthodontic retainer wires according to loading (0×, 1000× and 10,000× cycles) and submersion media.

	Non loaded	1000×	10,000×
Water			
Noninium	0.9 (0.1) ^{1,a}	1.9 (0.9) ^{2,a}	1.7 (1.3) ^{3,a}
Original Wildcat	0.6 (0.6) ¹	3.0 (2.5) ^{2,b}	5.3 (4.5) ^{4,b}
Lingual retainer	0.2 (0.1) ^{1,c}	1.1 (0.4) ^{2,c}	5.4 (2.0) ⁴
Dentaflex 3-s	1.3 (1.8) ¹	9.3 (2.0) ^d	9.0 (3.4) ^d
Dentaflex 6-s	4.8 (0.9) ^e	2.4 (1.2) ^{2,e,f}	1.9 (1.0) ^{3,f}
Lactic acid			
Noninium	12.1 (0.9) ^{2,c}	14.8 (2.1) ^{4,c}	13.7 (0.4) ^c
Original Wildcat	189.7 (1.9) ^{1,b}	280.6 (2.8) ^{3,a}	239.5 (2.4) ^{5,7,a,b}
Lingual retainer	26.0 (6.1) ^{2,d}	28.1 (5.8) ^{4,d}	44.2 (12.3) ^{7,d}
Dentaflex 3-s	131.8 (17.9) ^{1,e}	181.4 (42.1) ^e	163.2 (21.5) ^{6,e}
Dentaflex 6-s	263.5 (19.6) ^f	263.4 (28.2) ^{3,f}	226.5 (25.2) ^{5,6,f}

a–e Statistically significant difference within the wire between the different loadings.
 1–7 Statistically significant difference within the cyclic loading between the different wires.

composition of the Original Wildcat, Lingual retainer, Dentaflex 3-s, and Dentaflex 6-s is very similar, while Noninium contains mainly Fe, Cr and Mn and indeed Ni below the detection limit of the EDAX (ca. 0.2 wt%). The nickel release from the 5 studied wires in the different conditions is summarized in Table 2 and graphically depicted in Fig. 2. Three-way ANOVA showed that the type of wire ($F=109.9$; $p<0.001$), the different storage medium or pH ($F=801.3$; $p<0.001$), and mechanical loading ($F=3.5$; $p=0.032$) had a significant effect on the nickel release. The data were further analyzed per storage medium. In water, two-way ANOVA showed significant difference for the type of wire ($F=18.1$; $p<0.001$) and mechanical loading ($F=9.9$; $p<0.001$). In lactic acid, two-way ANOVA showed significant difference for the type of wire ($F=108.5$; $p<0.001$) but not for mechanical loading ($F=3.1$; $p=0.051$). The post hoc Tukey tests showing the individual significant differences between the wires and number of loading cycles are summarized in Table 2.

In Table 2 the absolute release in ppb is shown. These values, together with surface area of each wire summarized in Table 1, were used to calculate the nickel release in $\mu\text{g cm}^{-2} \text{ week}^{-1}$. These results are shown in Fig. 2 together with the release limit of $0.5 \mu\text{g cm}^{-2} \text{ week}^{-1}$ according to the EU Nickel Directive for the use of Nickel (94/27/EC).

4. Discussion

Variation of the pH or mechanical loading of orthodontic retention wires had significant effect on the leaching of metal ions. These results showed that mechanical loading had some influence on the measured Ni release, but pH is clearly a determining factor. Furthermore, it was shown that the investigated wires with similar composition, e.g. Lingual retainer, Original Wildcat, Dentaflex 3-s and Dentaflex 6-s, can have different Ni release rates and that the investigated “Ni-free” wire still contain some traces of Ni. The Ni release of the latter wire and the Lingual retainer (3M, Unitek) was similar. The type

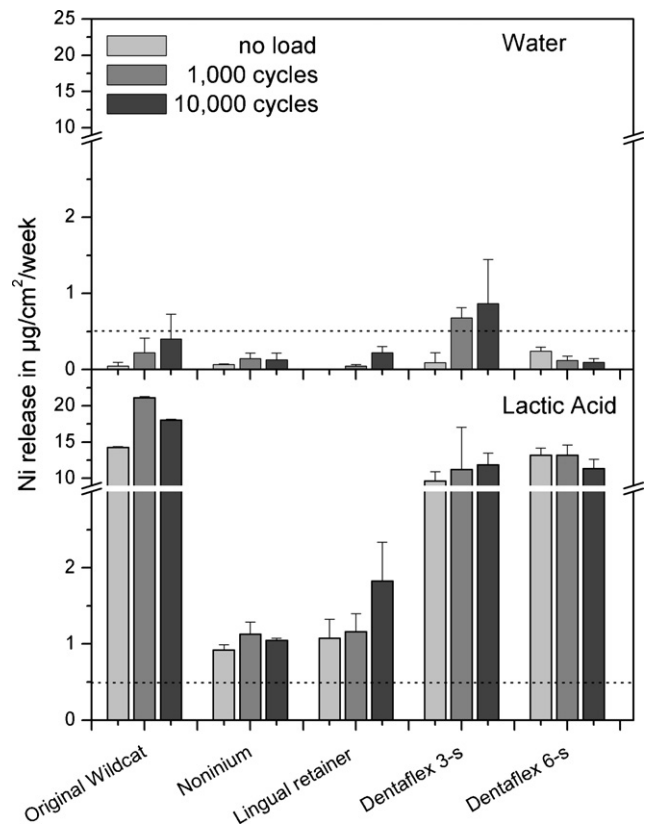


Fig. 2 – Graphic representation of the nickel release from the five studied wires according to loading and submersion medium. The dotted line depicts the reference value of Ni release accepted by the EU Nickel Directive for the skin ($0.5 \mu\text{g cm}^{-2} \text{ week}^{-1}$).

of wire, i.e., triple (Dentaflex 3-s) or six-stranded (Dentaflex 6-s), did not have a major effect on the Ni release. To our knowledge, the release of nickel from orthodontic retention wires was never reported. Besides Ni, other ions were released from the wires. Iron (Fe) and chromium (Cr) had the highest release values in a range of $0.01\text{--}23.4 \mu\text{g cm}^{-2} \text{ week}^{-1}$ and $0.01\text{--}30.26 \mu\text{g cm}^{-2} \text{ week}^{-1}$, respectively. However, the focus of this study was the nickel ion release.

Although there is no literature available for direct comparison, these wires should behave similar to arch wires, brackets, headgears, or simulators of the whole orthodontic appliance, which are made from similar materials. The results obtained in this study are in accordance with those from other authors, which used appliances made either from stainless steel or nickel–titanium (NiTi) alloys. Although all include dynamic conditions, the immersion media and the methods for analysis were different [8–10,18,19]. Noninium and Unitek stainless steel wires were tested in a mechanical and thermal setup by Arndt et al. [19]. The Ni release for Unitek, after exclusively mechanical loading in water, was similar to that obtained in our study, with $0.2 \mu\text{g cm}^{-2} \text{ week}^{-1}$ after 10,000 cycles. In their study the Noninium wire did not release detectable amounts of Ni while we observed a Ni release comparable with the release from the Lingual retainer (Unitek, 3M). Both Jia et al. [10] and Peitsch et al. [18], reported that

NiTi wires under dynamic loading release more Ni compared with statically immersed wires with values of loaded/non-loaded wires of $1.08 \mu\text{g cm}^{-2} \text{ week}^{-1}$ / $0.27 \mu\text{g cm}^{-2} \text{ week}^{-1}$ and $0.33 \mu\text{g cm}^{-2} \text{ week}^{-1}$ / $0.01 \mu\text{g cm}^{-2} \text{ week}^{-1}$, respectively. Furthermore, a simulator of a full mouth NiTi appliance released $38.76 \mu\text{g week}^{-1}$ / $14.96 \mu\text{g week}^{-1}$ in 0.9% NaCl for dynamic and static conditions, respectively [8]. For a stainless steel appliance in 0.05% NaCl, a nickel release of $280 \mu\text{g week}^{-1}$ was reported [20].

Stainless steel wires are considered to be safe in nickel allergic patients [3]. However, it was shown that stainless steel wires and orthodontic appliances release considerable amounts of Ni [8]. A “safety threshold” of Ni release without biological repercussions has not been considered up to now. Furthermore, it has been reported that in cases of hypersensitivity to orthodontic appliances, removal of the appliances clearly shows an improvement of the symptoms [2,14,21,22]. At the cellular level, other studies report that Ni-containing orthodontic appliances may induce DNA damage [23] or increase epithelial cell proliferation [24]. The gingival overgrowth associated with the orthodontic treatment is thus, not only often plaque-related, but may also be a consequence of the corrosion process [24].

Instead of using stainless steel wires, alternatives like Noninium can be used. Noninium wire is classified as a manganese-steel, “Ni-free” wire. However, slight traces of Ni can be included during the process of manufacturing (<0.2%). This explains the leaching of Ni in our samples. Other studies also found that the considered Ni-free wires release considerable amounts of Ni [5,19,25], which suggests a need for a cautious utilization of this wire. These Ni-free, manganese-steel wires, were shown not only to release Ni, but also to influence cellular metabolism by inhibiting cell proliferation [25] and inducing DNA damage [26]. Moreover, allergic contact dermatitis/stomatitis to manganese is reported in a few clinical cases [27–30].

All wires investigated in acid lactic and some in water in this study released a concentration of Ni higher than the EU Directive restricting the use of Nickel on the skin (94/27/EC). This directive states that “the rate of nickel release from products intended to come into direct and prolonged contact with the skin should not exceed $0.5 \mu\text{g cm}^{-2} \text{ week}^{-1}$ ”. However, retention wires do not contact with the skin or directly with the oral mucosa. The clinical implication of this study is that the investigated retention wires release metal ions that may induce allergic reactions. In this way, the choice for a metallic retainer must be carefully and conscientiously considered. The dentist/orthodontist must be aware of the reactions that a retainer may induce, either in patients with known or unknown history of hypersensitivity to metals. Furthermore, it was shown that the pH had a drastic effect on the Ni release, while loading had only a marginal effect. The abrupt drop of pH after each meal and the microbiological activity in plaque [9,17] contributes to periods of low pH. This reflects the importance of maintaining perfect oral hygiene to prevent the corrosion process.

In summary, to achieve teeth position stability, retention wires are used for a long and sometimes indefinite period of time. All investigated retention wires, i.e., Original Wildcat, Noninium, Lingual retainer, Dentaflax 3-s, and Dentaflax

6-s released Ni with a maximum of $21.08 \mu\text{g cm}^{-2} \text{ week}^{-1}$. The lowest Ni release was found for Noninium and Lingual retainer. Functional loading and, especially, pH strongly influence Ni release from metallic appliances in the oral cavity. Metal ions, especially nickel and chromium, are released continually and patients are continuously exposed to allergens that may be sufficient to elicit immune responses.

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