Influence of the Chemical Composition on the Mechanical Properties of Orthodontic Archwires

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This study was undertaken to evaluate the difference between the main mechanical properties (ultimate tensile strength (UTS), yield strength (YS), modulus of elasticity (E) and the load deflection characteristics of the stainless steel (SS) and nickel titanium (NiTi) orthodontic archwires. Forty archwires (20 NiTi and 20 SS) of two cross-sectional diameters (0.016 inch and 0.016x0.022 inch) were obtained from a single manufacturer. Tensile tests and three-point bending tests were performed on five samples of each type of archwire. Mann-Whitney test, level of significance p<0.05 was used to statistically analyzed the results. Statistical analysis was performed using GraphPad Prism 5.0 for Windows. The values obtained through tensile testing of the 2 archwire groups indicated superior strength for Stainless steel (group I) followed by Ni-TI (group II). The load deflection values obtained through three-point bend testing of wire specimens from groups I and II were highly significant for the rectangular wires. Statistically insignificant differences of the round section wires' deflection value were observed. It is evident from the data that stainless steel with high values for yield strength remains a mainstay in fixed orthodontic therapy. The rectangular NiTi archwire, appears to be kinder to the dento-alveolar tissues by generating low, consistent force, when compared to the rectangular SS alloy for load deflection characteristics.

Keywords: orthodontic archwire, stainless steel, nickel-titanium, modulus of elasticity

Fixed orthodontic therapy is based on the property of the teeth to be moved when a consistent and continuous force is applied. The amount of the generated force is determined by the mechanical properties of the inserted archwires. From a biomechanical point of view, the required forces must be low in magnitude and continuous in nature, in order to avoid root and periodontal membrane damage and to allow rapid and relatively painless tooth movement [1]. The three major alloys used in archwire fabrication are stailess steel, nickel-titanium and beta-titanium. Their different mechanical properties explain why each wire is indicated in a specific treatment phase [2]. In other words, orthodontic wire selection should take in consideration many factors: the transverse section of the wire, wire surface etc. A thorough knowledge of the wires requires a proper characterization of the alloys from both a mechanical and clinical point of view [3-5].

The three major properties of an archwire, which define their clinical usefulness, are: strength, stiffness and range; the connection between them is defined by the following relationship: strength= stiffness x range [3].The resilience (the energy storage capacity) and the formability (the amount of permanent deformation a wire can withstand) are also clinically important factors [2-4].

The SS alloys used as orthodontic wires are an austenitic type known as 316 L archwires (the L designation denotes a low carbon content) which contain approx. 18% Cr, and 8 % Ni (also the exact composition is not clearly mentioned by the manufacturer) [4,5].These archwires are considered as a reference material for comparing the characteristics of other types of orthodontic wires such as Ni-Ti and they are indicated in the treatment phases when a more rigid and less springback properties are needed [5]. The NiTi wires contain approx. equiatomic proportions of Ni and Ti, and their corrosion resistance is largely due to the presence of the Ti oxides formed on the surface of the wire [6-8]. The 2 major properties of the NiTi wires are their shape memory and superelasticity. Due to these properties, the NiTi wire became the preferred material for orthodontic applications in which a long range of activation with constant force is needed [8].

A very popular method to compare 2 archwires of various materials, sizes and dimensions is the use of ratios of their major properties (strength, stiffness and range) [3]. Numerous articles have addressed the study of the mechanical and structural properties of the SS and NiTi wires [1,6-19]. These articles evaluated tensile properties, bending characteristics and surface properties as part of the archwire alloy characterization. The findings represent an important factor in achieving better biomechanical characteristics and, it is also important for the clinicians to have reliable information about the used archwires.

Therefore, the aim of the present study was to investigate the main mechanical properties (ultimate tensile strength (UTS), yield strength (YS), modulus of elasticity (E) and

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Fig. 1. The Instron Universal Testing Machine

Fig. 2. Three point bending set-up for the load - deflection measurement

the load deflection characteristics) of the two types of clinically used ortodontic wires, and to compare the results in order to facilitate clinical wire selection.

Experimental part

Materials and methods

A total of 40 wires of the two alloys were selected (GAC International™) for this study. They represented various cross-sectional dimensions with round and rectangular shapes available only as preformed arches. The specimens of these wires were divided in three groups:

Group I: stainless steel

Group II: NiTi

The distal straight segments of each preformed arches were tested. The choice of only one manufacturer was made because the fabrication process and chemical composition of different manufacturers can affect the mechanical properties.

The tests were carried out on 2 different wires of cross-sectional dimensions and shapes: round 0.016 inches (0.406 mm) and rectangular 0.016x0.022 inches (0.406mm x0.558mm).

An Instron Universal Testing Machine type 3366, 10kN was used to perform the tests (fig. 1). The measured values were recorded for each specimen by the testing machine software Instron Bluehill 2. The collected data was exported in spreadsheet file format (Microsoft Excel).

Tensile stress at yield (0,2%), tensile stress at break and modulus of elasticity are determined using a standard tensile test for each group and shape of the wire. Five wires were tested individually. The span of the wire between crossheads was 40 mm and the crosshead speed of the machine was set to 1 mm/min for all tests. The load-displacement data obtained from the tensile test are used to get the stress-strain diagrams. Calculated values are the engineering strains and stresses, based on initial cross-sectional area of the specimens. The parameters were calculated using the next formulas: YS=yield load in N / cross-sectional area in mm^2, UTS= breaking load in N / cross-sectional area in mm^2.

In order to determine the load-deflection characteristics of the wires, each specimen was subjected to a three-point bending test [20]. The specimens were ligated with elastomeric ligatures in the slots of four edgewise brackets (3B STD Edgeweise, GAC International ™). These brackets were glued to an aluminum base, such a way that a 14 mm span was created between the internal sides of two adjacent brackets (fig. 2). The base was attached to the lower jaw of the machine. A metal blade, with a curvature of 1 mm of its extremity, was fixed to the upper jaw of the machine, to deflect the mid portion of each sample. Each SS and Ni-Ti wire was deflected 1 mm, at a deflection speed of 1mm/min and then was returned to its starting point at the same speed.

All the data obtained from the 2 tests described above were statistically analyzed. Descriptive analysis was made to determine the mean and standard deviation values. Mann-Whitney test was performed in order to compare the results. Statistically significant differences ($p<.05$) were evaluated for all measurements. Statistical analysis was performed using GraphPad Prism 5.0 for Windows.

Results and discussions

The values obtained through tensile testing of the two archwire groups indicated superior strength for Stainless Steel (group I) followed by Ni-TI (group II). Stress-strain curves for the SS archwires with 0.016" cross sectional dimensions are shown in figure 3. For steel archwires the offset yield point (proof stress) was calculated according to 0.2% of strain. The value of the ultimate tensile strength (UTS) of tested specimens is statistically not significant, but different values were obtained for the strain corresponding to maximum load.

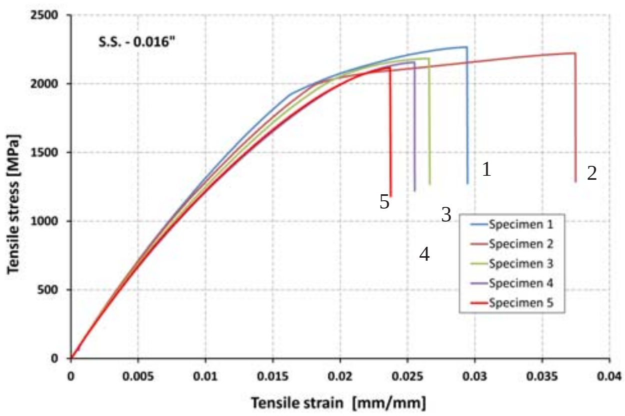

Fig. 3. Stress-strain diagrams for the 0.016" SS archwire specimens

The values for the mechanical properties (ultimate tensile strength (UTS), yield strength (YS) and modulus of elasticity (E)) of the two investigated groups are summarized in table 1 and 2 and they show as expected a significant difference for the yield strength and modulus of elasticity of the NiTi wire compared to the SS wire. Figure 4 shows the comparative strain –stress diagrams of the two groups of materials.

Table 1
TENSILE TEST RESULTS FOR 0.016" Ni-Ti AND SS WIRES

Archwire material / Mechanical propriety	Ni-Ti	SS
	Mean value (Std. dev.)	Mean value (Std. dev.)
Yield Stress [MPa]	336.9 (6.43)	293 (6.77)
Ultimate Tensile Stress [MPa]	1257.3 (25.33)	2188 (58.14)
Modulus of elasticity [MPa]	30187 (1932)	113279 (5515)

Table 2
TENSILE TEST RESULTS FOR 0.016 x0.022" Ni-Ti AND SS WIRES

Archwire material / Mechanical propriety	Ni-Ti	SS
	Mean value (Std.dev.)	Mean value (Std.dev.)
Yield Stress [MPa]	320.7 (30.9)	296.96 (15.26)
Ultimate Tensile Stress [MPa]	1252 (23.14)	1913 (18.38)
Modulus of elasticity [MPa]	24837 (1227)	133265 (6255)

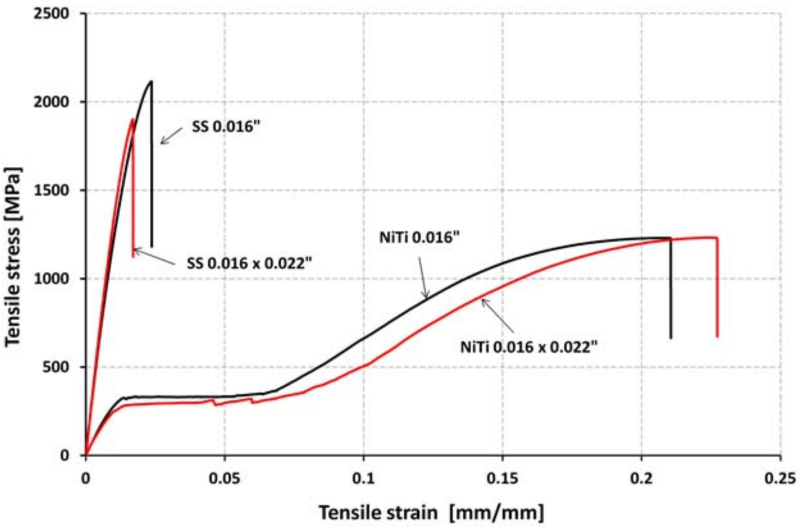

Fig. 4. Stress-strain diagrams for the SS & Ni-Ti wires

Comparing the archwires of the same material it can be noticed a closer behaviour during the tensile tests. The slightly different values of the materials constant E and ultimate tensile stress that occurred between the two cross sectional shapes are supposed due in principal to the performing and fabrication (wire-drawing) process of the archwhires.

Means and standard deviations of activation and deactivation forces of the wires measured at a deflection of 1 mm are listed in table 3. Comparative load-deflection behaviour of investigated archwires is illustrated in figure 5. Activation and deactivation deflections of 0.5 mm were selected to establish a comparison parameter at the midpoint of the loading and unloading deflection used in this study.

The load deflection values obtained through three-point bend testing of wire specimens from groups I and II were highly significant for the rectangular wires. Statistically insignificant differences of the round section wires' deflection value were observed.

Characterization of different archwires from the point of view of their mechanical properties is extremely important in understanding their behaviour in a clinical situation. Knowing what does a specific archwire do well and what does it do poorly in an everyday practice helps the orthodontists selecting the perfect archwire from an indefinitely amount of orthodontic archwires available on the market. The present study was aimed to characterize the two most commonly used alloys in orthodontics: SS and Ni-Ti. Beta-titanium, chromium-cobalt and other archwire alloys were not subject in this study.

Despite the fact that laboratory tests do not necessarily reflect the clinical situation, they provide a basis for comparision of different wires and are used in many studies [1, 6-19] in the literature. The tensile tests are helpful to investigate the stress-strain behaviour of a wire, which is used to define both the ultimate tensile strength UTS (the maximum engineering strength experienced by a material in tension) and the modulus of elasticity E (the engineering property of a material that equals the ratio of stress to strain, when deformation is totally elastic) [2,4].

The values of the modulus of elasticity (133 GPa) and ultimate tensile strength (1913 MPa) of the rectangular SS wires resulted from this study are less than results of previous investigations. SS wire presented modulus around 170 GPa, in one study and 173 GPa in another, whereas the ultimate tensile strength reported was 2100 MPa. This could be explained by the differences of the archwires due to the manufacturer. Some studies [11] observed great variation in values with different SS wires of the same diameter, indicating that the wires are intrinsically different. Regarding strength, the YS of wires can differ noticeably

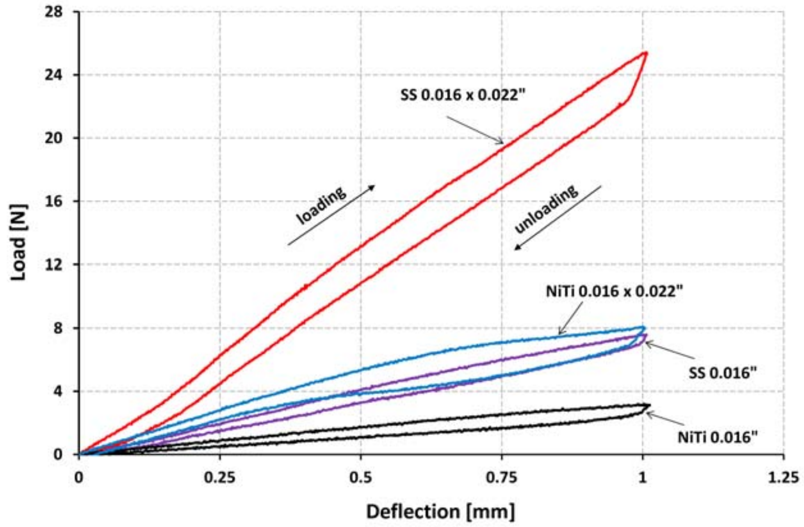

Fig.5. Load-deflection curves of investigated archwires during activation and deactivation

Table 3
MEAN VALUES FOR LOAD-DEFLECTION RATE OF INVESTIGATED WIRE SPECIMENS

Sample	SS 0.016	Ni-Ti 0.016	SS 0.016x0.022	Ni-Ti 0.016x0.022
0.5 mm loading (st.dev.)	4.01 (0.17)	1.81 (0.086)	13.15 (0.032)	5.51 (0.18)
1 mm loading (st.dev.)	7.46 (0.21)	3.01 (0.19)	24.60 (0.90)	7.86 (0.32)
0.5 mm unloading (st.dev.)	3.22 (0.15)	1.13 (0.095)	10.39 (0.72)	3.65 (0.19)

between manufacturers and even between wire sizes within a product line due to strain hardening during the wire-drawing process [9].

Based on various modes of bending and tensile tests performed on as-received products YS of the NiTi wires averaged 410 MPa while E averaged 34 GPa [4]. In our study the YS and E modulus show similar values for the NITi wires (328 MPa and 27 GPa respectivelly).

The stress strain behaviour of the NiTi wire, obtained by the tensile test indicates the clinical performance of the wire in terms of load deflection rate, working range, stiffness, and resilience [3,6]. In the present study, both the round and rectangular NiTi wires exhibit higher yield strength, when compared to the SS wires.

One of the most important parameter which helps to determine the biologic nature of tooth movement are the load-deflection characteristics obtained from the three-point bending test[2]. The advantage of this test, compared to the Olsen stiffness tester, is that it is simply to perform in the laboratory [5]. This test was chosen mainly because of its close simulation to clinical application, reproducible results, and the ability to differentiate wires with superelastic properties. The results of present study clearly indicated the kinder nature of NiTi archwires to tooth as well as supporting tissues, as evidenced from the low values needed to deflect the wire and simulate engagement of the wire in the bracket of a misaligned tooth. Stainless steel was the more rigid among the archwire alloys with very high loading values and less spring back properties.

The level of force and stiffness and their dependence on cross-sectional dimension was also evaluated in this study. The round 0.016 inch wires showed a lower loading and unloading force when compared to the rectangular 0.016x0.022 inch wires. For the same maximum deformation, the force increases with the cross-sectional dimension. From a clinical point of view, it is important, because smaller wires, deliver lower forces to the periodontal structures.

The corrosion of the orthodontic archwires was studied in [21].

Conclusions

It is evident from the data that stainless steel with high values for yield strength remains a mainstay in fixed orthodontic therapy. The rectangular NiTi archwire, appears to be kinder to tissues by generating low, consistent force, when compared to the rectangular SS alloy for load deflection characteristics.

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