Mechanical Properties of Copper-Nickel-Titanium Archwires

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MECHANICAL PROPERTIES OF COPPER-NICKEL-TITANIUM ORTHODONTIC WIRES

by

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ABSTRACT

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Introduction: The initial phase of orthodontic therapy relies on flexible wires, usually composed of a nickel-titanium alloy, to apply a substantially constant load during tooth movement. Copper has been added to nickel-titanium archwires, resulting in an alloy with potential clinical advantages such as a lower stress hysteresis. Many orthodontic companies claim that their copper-nickel-titanium manufacturing process allows for the production of more consistent transition temperatures in the wires, allowing the orthodontist to customize treatment to various patients based on the force level needed. There are currently many manufacturers of these wires, creating a wide range of copper-nickel-titanium archwires from which orthodontists may choose. The goal of this research study was to test various manufacturers' copper-nickel-titanium archwires to see if their mechanical properties are comparable to each other.

Materials and Methods: Six different companies' copper-nickel-titanium archwires wires were tested: Ormco, American Orthodontics, Dentsply GAC, Ortho Organizers, Rocky Mountain Orthodontics, and Ortho Technology. Within each of the 6 brands, 0.018" round and 0.016" x 0.022" rectangular wires at both 27˚C and 35˚C transition temperatures were identified. Three-point bending test was utilized to determine the activation and deactivation forces present within segments of the various wires. Forces for the deflection were recorded directly onto the computer software program. Data were compared using one-way analysis of variance at a 0.05 significance level with a Tukey's HSD test post hoc analysis, when required.

Results: Statistically significant differences were observed in force levels between brands for all round and rectangular wire/temperature combinations. Overall, within both 27˚C and 35˚C and both round and rectangular wires, Ormco tended to behave the most uniquely when compared to all of the other brands.

Conclusions: Wires of the same materials, dimensions, and transition temperature but from different manufacturers do not always have the same mechanical properties. Improvements should be made in the standardization of the manufacturing process of copper-nickel-titanium archwires in order to provide orthodontists with CuNiTi archwires that have consistent mechanical properties.

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CHAPTER 1
INTRODUCTION

Orthodontics is a specialty area in dentistry, which focuses on correcting malocclusions. A malocclusion is defined as a misalignment or incorrect relationship between the teeth of the two dental arches when they approach each other as the jaws close. The term was coined by Dr. Edward Angle who is known as the “Father of Modern Orthodontics”. Malocclusion of some form is present in the majority of the population, and attempts made to correct mal-aligned teeth trace back to at least 1000 B.C. Orthodontic treatment goals include achieving an esthetic, stable, and functional occlusion, while simultaneously attaining an ideal facial balance (Proffit et al., 2013).

Wires have been a mainstay in orthodontic treatment since its infancy. Wires composed of various materials are utilized with an assortment of fixed as well as removable appliances to correct malocclusions. Archwires engaged into brackets bonded onto individual teeth effectively transmit forces to the dentition, ultimately resulting in tooth movement (Kusy, 1997; Proffit et al., 2013).

Not just one ideal archwire is used to execute orthodontic therapy. In most orthodontic cases, a progression of various archwires fabricated from different materials are used. The initial phase of orthodontic therapy, known as leveling and aligning, relies on flexible wires, typically composed of a nickel-titanium alloy. Nickel-titanium boasts qualities such as high spring-back and a low elastic modulus (Nikolai, 1997; Proffit et al., 2013). Once initial leveling and alignment is completed, stiffer wires, usually composed of stainless steel, are used to finish and detail a case. This is in part due to stainless steel's properties of low friction, good formability, and a high elastic modulus (Kusy, 1997; Proffit et al., 2013).

Nickel-titanium was first developed in the late 1950s. Although not initially developed for orthodontics in particular, the specialty area soon recognized its potential clinical advantages in leveling and aligning the dentition. This is due to nickel-titanium's unique, "shape memory" and "superelastic" qualities. These archwires are able to apply a substantially constant load during movement of the teeth, thus improving efficiency of the orthodontic procedure. Furthermore, a constant force transmitted to the dentition over a long activation period results in a desirable biologic response (Proffit et al., 2013).

Various nickel-titanium alloys have been developed by the addition of a third element to nickel-titanium. These alloys can exist in two different crystal structures: martensite and austenite. At low temperatures and higher stress, the martensitic form is more stable, and at higher temperatures and lower stress, the austenitic form is more stable. The transition between these two phases/structures is fully reversible and typically occurs at low temperatures. If the wire is cooled below the transition temperature, it will transform into the martensite form, and it can plastically deform. Once it is heated back up to the transition temperature, however, the wire will return back to the austenite phase and return to its original form, thus making this wire very clinically effective for initial leveling and aligning of the dentition (Santoro et al., 2001).

Copper is one of the third elements that has been added to nickel-titanium, resulting in a copper-nickel-titanium alloy with many potential clinical advantages in orthodontics. Manufacturing companies claim that the addition of copper would allow the orthodontist to more easily engage larger archwires earlier in treatment to mal-aligned teeth. This is because the copper lowers the loading stress while still providing relatively high unloading stress resulting in more effective orthodontic tooth movement of teeth. This is known as having a lower stress hysteresis (Gil and Planell, 1999; Sachdeva et al., 1991).

A variety of orthodontic companies claim that the copper-nickel-titanium manufacturing process allows for the production of more consistent transition temperatures in the wires. They state that this has the clinical advantage of allowing the orthodontist to customize treatment to various patients by choosing between specific different amounts of force correlated to transition temperatures, i.e. 27˚C, 35˚C, or 40˚C. This has clinical significance in customizing treatment to different patients, because many factors have been shown to affect oral cavity temperature. These include variation in body core temperature, ambient temperature and humidity, mouth-breathing, intake of food and fluids, smoking, and whether the mouth is open or closed (Barnes, 1967; Boehm, 1972; Sloan and Keatinge, 1975; Zehner and Terndrup, 1991; Longman and Pearson, 1987; Terndrup et al., 1989; Michailesco et al., 1995; Mairiaux et al., 1983; Cooper and Abrams, 1984; Volchansky and Cleaton-Jones, 1994). Although many manufactures of these copper-nickel-titanium wires state that through their manufacturing process they are able to provide specific mechanical properties, there is a lack of evidence comparing the various brands' wires' to each other. Thus, the goal of this study was to test various manufacturers' copper-nickel-titanium archwires to see if their mechanical properties are comparable[A1].

CHAPTER 2
LITERATURE REVIEW

Introduction to Orthodontic Wires

Wires have been a cornerstone of orthodontic treatment since the establishment of the profession. Orthodontic wires are fabricated from a variety of different materials, and can be produced in an assortment of shapes as well. Wires can be straight, multi-stranded, or formed into a helical coil or spring shape. The variety of materials and shapes allows for a multitude of clinical applications of the wires. For example: a straight wire can be engaged into brackets which are bonded to the teeth, springs can be incorporated into a removable appliance to correct the malocclusions of just a single tooth, multi-stranded wires can be bonded to the lingual surfaces of the teeth in order to provide a means of permanent retention, and ligature wires can be used to join individual teeth into a unit to provide anchorage (Kusy, 1997; Proffit et al., 2013).

The most commonly used shape of wire in contemporary orthodontics is the archwire. When the "Father of Modern Orthodontics", Edward Angle, introduced the edgewise appliance in orthodontics in the 1920s, archwires quickly gained popularity. They are still the most frequently used type of wire in orthodontics today. Archwires are pre-fabricated in the shape of an ideal dental arch and can be engaged into brackets that are bonded onto the individual teeth. When the archwire is engaged into the brackets, it delivers the necessary forces to level and align teeth. The archwire thus transmits forces to the dentition, resulting in tooth movement (Proffit et al., 2013).

Tooth Movement

Optimum orthodontic movement is produced by light, continuous forces. These light, continuous forces are the most efficient and biologically safe method of tooth movement. Using too heavy of an orthodontic force risks pulp vitality as well as root resorption, not to mention, it is not as efficient. Light, continuous forces maintain a relatively constant pressure in the periodontal ligament during tooth movement. Forces that are too high in magnitude would lead to hyalinization of the periodontal ligament, and may cause irreversible damage such as root resorption (Reitan, 1957; Storey, 1973). Therefore, optimum force levels for orthodontic tooth movement should be high enough to stimulate cellular activity, yet, not too high as to occlude blood vessels in the periodontal ligament.

The key to producing orthodontic tooth movement efficiently is the application of a sustained force. The force must be applied for a considerable percentage of the day. Animal experiments suggest that only after a force is maintained for approximately 4 hours do cyclic nucleotide levels in the periodontal ligament increase. Clinical experience suggests that effective tooth movement is produced when a force is maintained for a longer duration (Meeran, 2012).

If a light, continuous force is applied, a relatively smooth progression of tooth movement will result from frontal resorption. However, if a continuous heavy force is applied, tooth movement will be delayed due to undermining resorption instead of frontal resorption. As a result, heavy, continuous forces are to be avoided in orthodontics (Meeran, 2012; Proffit et al., 2013).

Archwires in Orthodontics

The properties of an ideal archwire for efficient orthodontic movement can be defined based off the biomechanical principle that light, continuous forces produce the most biologically efficient tooth movement. These properties include: 1. high strength, 2. low stiffness, 3. high range, 4. high formability, and 5. affordability. In addition, the archwires should be weldable or solderable so that hooks or stops can be attached to the wire if needed. Not just one single archwire material, however, meets all of the aforementioned requirements. As a result, a series of different archwires made out of various materials are used as treatment progresses to accomplish the multiple goals of the individual phases of orthodontic treatment including leveling and aligning, space closure and A/P correction, detailing and finishing, and retention (Kusy, 1997).

In the early 1900s, during the beginning of the “archwire era of orthodontics”, noble metal alloys, such as gold, were primarily used for orthodontic wires. This is because nothing else would withstand intra-oral conditions. However, in the 1930s, with the introduction of different alloys with lower cost and better mechanical properties, the initial noble metal alloy archwires became obsolete in modern day orthodontics. Today, the three main categories of orthodontic archwires that have replaced the noble metal alloys include: stainless steel, beta titanium, and nickel-titanium (Kusy, 1997).

Stainless steel archwires became broadly accepted within orthodontics by the 1960s. Stainless steel has greater strength and springiness than the pioneer wires in orthodontics; the noble metal alloys. Additionally, it also has the beneficial property of corrosion resistance, which is due to its high chromium content. The chromium forms a thin oxide layer that prevents the diffusion of oxygen. Stainless steel is commonly used in the later stages of orthodontic treatment for leveling, detailing, and finishing due to its properties of low friction, good formability, stiffness, and less spring-back compared to some of the other categories of archwires (Proffit et al., 2003).

Beta-titanium wires are titanium molybdenum alloys that were introduced for orthodontic use in 1979 by Goldberg and Burstone. Beta-titanium archwires, commonly referred to as TMA archwires after the first commercially available version, have advantages such as low elastic modulus, excellent formability, weldability, good spring-back, and a low potential for hypersensitivity. However, the use of beta-titanium wires has disadvantages such as (1) high surface roughness, which increases friction at the wire-bracket interface during the wire sliding process, and (2) susceptibility to fracture during bending. With properties in between nickel-titanium and stainless steel, these wires are used commonly as an intermediate wire between the two. As a result, many clinicians use this wire as their main "working wire" during orthodontic treatment (Kusy, 1997).

Nickel-titanium is the final category of wires used in modern orthodontics. Nickel-titanium, commonly referred to as "NiTi," was first discovered in the late 1950s by the U. S. Naval Ordnance Laboratory (NOL). It was developed by the space program, and was known as "Nitinol." Although not initially developed for orthodontics, its clinical advantages in leveling and aligning teeth was soon noticed. Nickel-titanium archwires are known in orthodontics for their exceptional springiness and strength as well as their poor formability. As a result, nickel-titanium is extremely useful during initial orthodontic alignment of the teeth due to its ability to apply a light force over a large range of activation (Proffit et al., 2003).

Nickel-Titanium Properties

Nickel-titanium alloy's clinical advantages in orthodontics are based upon the fact that these alloys can exist in two different crystal structures: martensite and austenite. At low temperatures and higher stress, the martensitic form is more stable, and at higher temperatures and lower stress, the austenitic form is more stable. The transition between these two phases/structures is fully reversible and occurs at low temperatures. The two different phases of nickel-titanium are responsible for two clinically significant properties of nickel-titanium: shape memory and superelasticity (Burstone et al., 1985; Miura et al., 1986).

Shape memory refers to the ability of the wire to return to its original shape after being plastically deformed. If the wire is cooled below the transition temperature, it will transform into the martensite form, and it can plastically deform. Once it is heated back above the transition temperature, the wire will return back to the austenite phase and return to its original form. Shape memory refers to the temperature-induced change in crystal structure, and it is also known as thermoelasticity (Fernandes et al., 2001).

Superelasticity refers to the large, reversible strains that the nickel-titanium wires can withstand due to the martensite-austenite transition. This property, also referred to as pseudoelasticity, is possible because the transition temperature between the two crystal phases is very close to room temperature. This property is evident in the almost flat section of the load-deflection curve. Clinically, this is a useful property in that the initial archwire can exert the same force, whether it was deflected a small or large distance (Fernandes et al., 2001).

Copper-Nickel-Titanium Archwires

Since the introduction of nickel-titanium archwires into orthodontics, a couple of different chemical elements have been added to the nickel-titanium in order to derive clinical advantages. One of the chemical elements that has been added to nickel-titanium is copper.

In 1991, Ormco applied for a patent for copper-nickel-titanium archwires, stating that the reason for the production of this wire was that there were some limitations associated with the existing nickel-titanium archwires commonly used in orthodontics. The first limitation stated by Ormco was that the amount of force applied by the NiTi orthodontic archwire to the orthodontic bracket is relatively low thus requiring longer treatment time. The second problem stated that the initial force necessary to engage the wire with the orthodontic bracket is quite high, thus making it difficult for the orthodontist to apply the archwire to the bracket, especially if the tooth is severely mal-aligned. The final problem listed by Ormco was that the substantially constant load is effective for only a relatively short distance and at a relatively low level of force. Ormco stated that they discovered that by controlling the composition of the shape memory alloy, with the addition of copper, the previously mentioned disadvantages of shape memory archwires could be eliminated or minimized. Therefore, Ormco claims that with the addition of copper to the nickel-titanium archwires, the archwires would have a lower loading stress while still providing relatively high unloading stress for more effective orthodontic tooth movement of teeth. Thus, the wires would deliver more force per tooth movement, and maintain a substantially constant force as the teeth move closer to their intended position (Sachdeva et al., 1991).

Since Ormco's patent on copper-nickel-titanium archwires expired, most of the major orthodontic companies have begun producing their own version of the copper-nickel-titanium archwire. Copper-nickel-titanium archwires are commonly marketed by these companies to orthodontists by stating that they exhibit a more constant force/deformation relationship, thereby providing superior consistency from archwire to archwire. Companies claim that these archwires demonstrate consistent transformation temperatures, ensuring consistency of force from batch to batch. Furthermore, they claim that this property allows the orthodontist to customize treatment to various patients by choosing between specific different amounts of force correlated to transition temperatures, i.e. 27˚C, 35˚C, or 40˚C.

These claims have been tested in vitro. Gil and Planell (1999) compared copper-nickel-titanium and nickel-titanium with respect to various properties such as transformation temperature, superelasticity, and load cycling behavior. They found that the addition of copper to a nickel-titanium alloy produces greater stability of both the transition temperature and the force applied to the teeth. The addition of small concentrations of third elements to nickel-titanium resulted in a large change in the Ms temperature. Therefore, with nickel-titanium alone, controllable adjustments of Ms are not easily achieved. However, it was found that adding even larger concentrations of copper to the nickel-titanium does not change the Ms temperature significantly. Their results show that small chemical composition changes produce large variations in the transformation temperatures for nickel-titanium alloys. However, for copper-nickel-titanium alloys, the transformation temperatures are much more stable in relation to changes in the chemical composition. A lower concentration-dependent Ms allows for easier production of commercial quantities of material having controlled Ms for thermal sensor and actuator uses. Furthermore, calorimetric measurements indicate that alloys with copper have substantially narrower hysteresis than nickel-titanium alone. Overall, it was found that the addition of copper was effective in narrowing the stress hysteresis and in stabilizing the superelasticity characteristics against cyclic deformation, with the result that the slope of the load-deflection unloading curve of the alloy is lower than nickel-titanium.

It is easy for a clinician to assume that all copper-nickel-titanium wires of the same type from the same manufacturer have the same mechanical properties. Research has been conducted to determine if this is in fact true. Pompei-Reynolds and Kanavakis (2014) sought to test the potential variability in mechanical and thermal properties among copper-nickel-titanium wires with the same advertised characteristics from their company. When this study was conducted, copper-nickel-titanium archwires were only commercially available from two companies: Rocky Mountain Orthodontics and Ormco. The results of the 3-point bend test showed statistically significant differences between manufacturers in interlot force delivery variations on unloading. When interlot force variations are large, it is questionable if the orthodontist can rely on the same clinical properties. The study confirmed that interlot variations exist between copper-nickel-titanium archwires of the same type from the same manufacturer (Pompei-Reynolds and Kanavakis, 2014).

CHAPTER 3

MATERIALS AND METHODS

Six different companies were identified as producing their own version of copper-nickel-titanium archwires. These 6 wires were: Ormco's Copper Ni-Ti (Orange, CA), American Orthodontics' (AO) Tanzo Copper Nickel Titanium (Sheboygan, WI), GAC's Copperloy (York, PA), Ortho Organizers' (Org) Nitanium (Carlsbad, CA), Rocky Mountain Orthodontics' (RMO) FLI Copper Nickel Titanium (Denver, CO), and Ortho Technology's (Tech) TruFlex Nickel Titanium archwires (Tampa, FL).

All six of these different companies produced their particular copper-nickel-titanium archwire in both round and rectangular shapes. Within both the round and rectangular shapes, various sizes were available among the brands. For consistency, one round diameter wire size and one rectangular wire size were chosen in order to allow for comparison of properties. The sizes: 0.018 inch round and 0.016 x 0.022 inch rectangular were selected because all six companies produced these particular sizes and additionally, these were selected because these wire sizes are commonly used clinically.

Two different transition temperatures were chosen, 35˚C and 27˚C, because both of these temperatures were produced in both 0.018" and 0.016" x 0.022" among the 6 different brands.

It is important to note that the 20 segments of each wire tested in each category for the particular brand were from the same production lot, eliminating the possibility of inter-lot variability amongst the wires.

The three-point bend test was utilized to test the various wires in accordance with the ISO 15841 standard for orthodontic wires with the exception that the bottom support span was 14 mm rather than 10 mm due to fixture limitations (ISO, 2014). The three point bending test is identified as the most appropriate test for force-deflection tests. It test segments of wires in order to determine the activation (loading) and deactivation (unloading forces) present within the wire. Wire segments of each of the four different wire size/temperature combinations were cut (n=20/size/temp). The same investigator cut all wire segments. Forces for the deflection were recorded directly onto the computer software program. Appropriate statistical analyses were utilized for each test when indicated.

The three-point bending test allows one to analyze the bending forces for a given deflection for all of the various wires. The test was conducted at intraoral temperature of 37°C. A 25 mm segment of each wire was utilized. Materials were tested in the condition they were received from the manufacturer. In order to test the straightest portion from the preformed archwires, segments were taken from the most distal segment of the archwires.

Wires were deflected with the universal testing machine (Instron, Canton, MA) at a rate of 2 mm/min to a mid-span deflection of 3.1 mm (Figure 1) and then reversed. The space between lower supports was 14 mm, with the upper member being centered at 7 mm (Figure 2). Force was monitored during loading and unloading (Figure 3). The linear slope was measured from the collected data and converted to bending modulus (Segal et al., 2009; Ballard et al., 2012). In addition, activation and deactivation bending force values at 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 mm were obtained from the test for comparison. Due to significant interactions among all three variables (brand/size/temperature) using three-way analysis of variance (ANOVA), data among brands were compared using one-way ANOVA for each wire size/temperature combination at a 0.05 significance level with a Tukey's HSD (honest significant difference) test post hoc analysis, when required. Statistical analysis was performed using SAS software (SAS Institute Inc., Cary, NC).

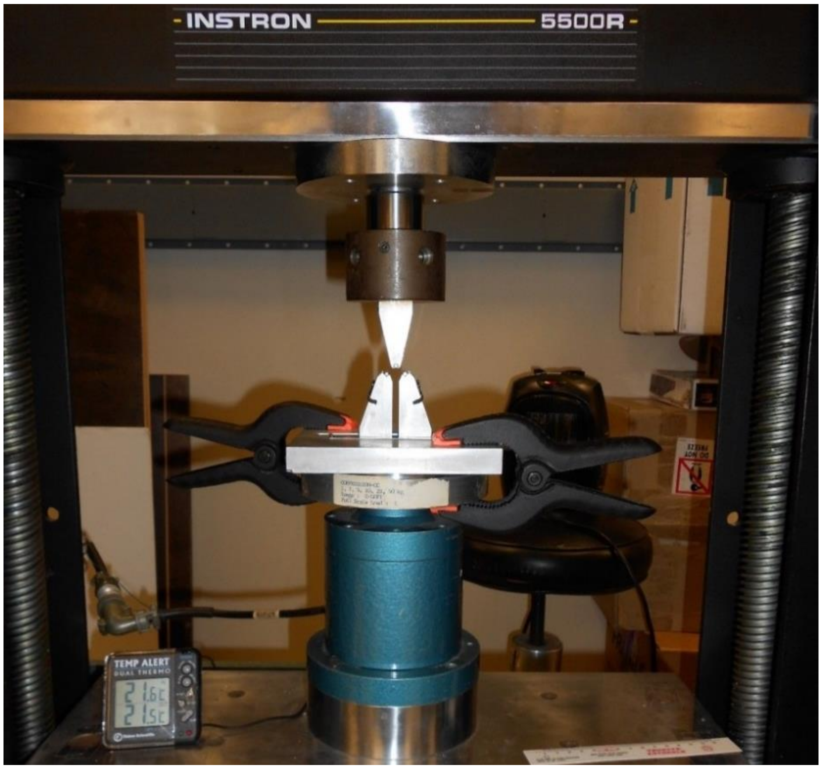

Figure 1. Instron 5500R utilized for data collection during the three-point bending test

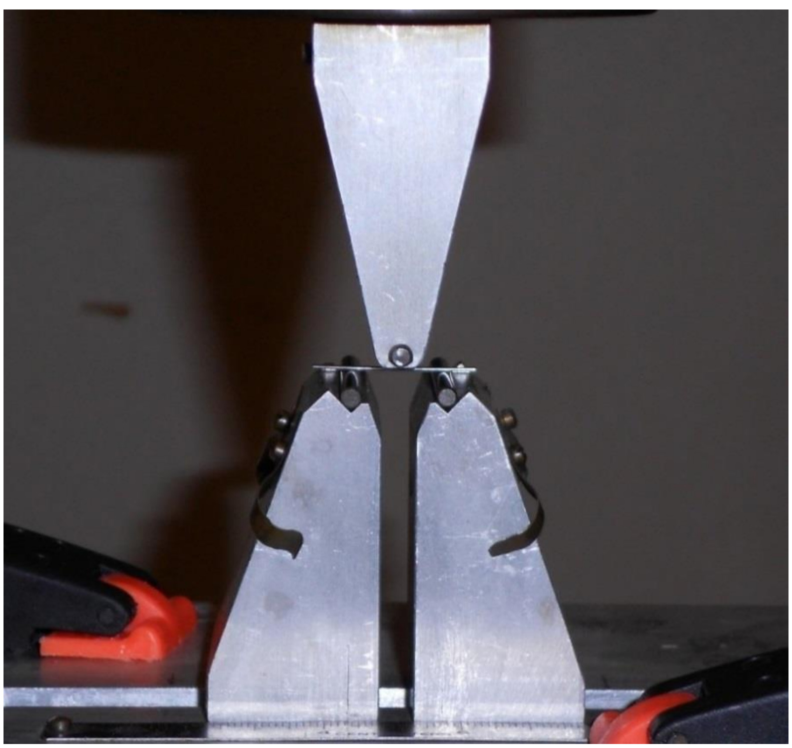

Figure 2. Testing set-up for three-point bending. A 14 mm span length between lower supports was used with the upper beam centered at 7 mm.

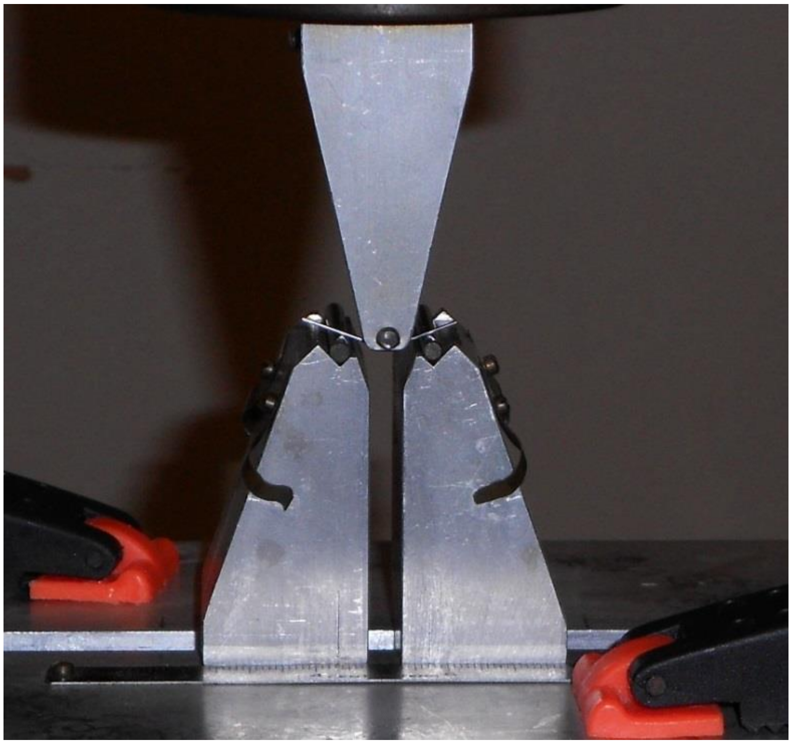

Figure 3. Three-point bending test in progress.

CHAPTER 4
RESULTS

When comparing the six different brands within round 35˚C wires, statistically significant ($p<0.05$) differences exist. When comparing the six different brands within round 27˚C wires, statistically significant differences also exist. Within both of these categories (round 35˚C and round 27˚C), some wires were found to be more similar to others. Individual differences between the brands are displayed by having common letters in Tables 1-4. Within round 35˚C and round 27˚C wires, Ormco tends to be the brand with the greatest differences when compared to all of the other brands.

When comparing the different brands within rectangular 27˚C wires, statistically significant differences ($p<0.05$) exist. Additionally, when comparing the different brands within rectangular 35˚C wires, statistically significant differences also exist. Within both of these categories (rectangular 27˚C and rectangular 35˚C), some wires were found to be more similar to others. Individual differences between the brands are displayed by having common letters in Tables 5-8. Within both categories, rectangular 27˚C and rectangular 35˚C wires, Ormco and American Orthodontics both appeared to be the most different when compared to the other brands.

Overall, within both 27˚C and 35˚C and both round and rectangular wires, Ormco wires tended to behave the most uniquely, meaning having force values different from the majority of the other brands.

Table 1. Bending values during activation of 0.018", 35°C wires.

Wire	ACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 1 mm (g)	Force at 2 mm (g)	Force at 3 mm (g)
Ormco	261±4 ABC	68.1±1.0 ABC	199±6 A	229±6 A	247±8 A
AO	276±6 A	72.0±1.5 A	159±4 B	178±4 B	187±5 B
GAC	268±3 C	70.0±0.7 C	153±3 C	167±3 C	172±4 C
Org	272±3 AB	71.2±0.9 AB	156±5 BC	170±6 C	176±6 C
RMO	257±4 BC	67.2±1.1 BC	146±4 D	160±4 D	164±5 D
Tech	268±6 ABC	70.1±1.4 ABC	155±7 BC	169±7 C	176±7 C

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 2. Bending values during deactivation of 0.018”, 35ºC wires.

Wire	DEACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 3 mm (g)	Force at 2 mm (g)	Force at 1 mm (g)
Ormco	242±5 B	63.2±1.4 B	221±7 A	162±5 A	138±6 A
AO	258±5 A	67.5±1.4 A	158±3 B	97±3 B	84±3 B
GAC	251±8 AB	64.8±4.0 AB	143±4 C	87±4 C	78±4 C
Org	255±7 AB	66.5±1.8 AB	146±6 C	88±7 C	77±7 C
RMO	243±5 B	63.4±1.2 B	136±5 D	81±5 D	72±6 D
Tech	251±11 AB	65.6±2.8 AB	146±7 C	91±8 C	82±7 BC

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 3. Bending values during activation of 0.018", 27^{o}C wires.

Wire	ACTIVATION				
	Stiffness (g/mm)	**Modulus (GPa)**	**Force at 1 mm (g)**	**Force at 2 mm (g)**	**Force at 3 mm (g)**
Ormco	276±5 CD	72.1±1.3 CD	207±3 A	238±4 A	255±6 A
AO	275±4 CD	71.9±1.1 CD	182±4 B	204±5 B	213±6 B
GAC	284±10 AB	74.2±2.6 AB	166±6 D	185±7 D	195±6 D
Org	270±5 D	70.6±1.3 D	174±3 C	192±4 C	199±5 CD
RMO	280±12 BC	73.2±3.0 BC	176±4 C	195±4 C	203±5 C
Tech	286±8 A	74.8±2.1 A	174±5 C	193±6 C	202±7C

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 4. Bending values during deactivation of 0.018”, 27°C wires.

Wire	DEACTIVATION				
	Stiffness (g/mm)	**Modulus (GPa)**	**Force at 3 mm (g)**	**Force at 2 mm (g)**	**Force at 1 mm (g)**
Ormco	257±8 BC	67.2±2.2 BC	229±4 A	169±3 A	148±3 A
AO	259±3 ABC	67.6±0.7 ABC	186±6 B	132±4 B	118±5 B
GAC	263±13 AB	68.7±3.3 AB	162±6 D	94±5 F	80±4 F
Org	253±4 D	66.0±1.1 D	173±4 C	120±4 C	108±3 C
RMO	261±7 AB	68.2±1.9 AB	176±4 C	116±7 D	102±8 D
Tech	266±6 A	69.4±1.6 A	173±6 C	103±5 E	87±4 E

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 5. Bending values during activation of 0.016”x 0.022”, 27^{o}C wires.

Wire	ACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 1 mm (g)	Force at 2 mm (g)	Force at 3 mm (g)
Ormco	386±10 C	69.2±1.8 C	252±11 A	284±13 A	297±13 A
AO	418±9 A	75.0±1.6 A	238±6 B	267±8 B	281±10 B
GAC	372±5 D	66.8±0.9 D	231±6 C	257±6 C	267±6 C
Org	383±11 C	68.6±1.9 C	235±6 BC	262±6 BC	273±7 BC
RMO	403±11 B	72.2±1.9 B	238±7 B	266±8 B	277±7 B
Tech	404±9 B	72.3±1.6 B	240±4 B	268±5 B	279±7 B

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 6. Bending values during deactivation of 0.016”x 0.022”, 27ºC wires.

Wire	DEACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 3 mm (g)	Force at 2 mm (g)	Force at 1 mm (g)
Ormco	368±10 C	65.9±1.7 C	265±12 A	180±11 A	159±11 A
AO	401±10 A	71.8±1.8 A	245±9 B	156±7 B	139±8 B
GAC	357±5 D	63.9±0.8 D	234±6 C	153±7 B	136±7 B
Org	367±8 C	65.7±1.4 C	239±6 BC	154±8 B	136±9 B
RMO	380±9 B	68.1±1.7 B	242±7 B	139±6 C	119±6 C
Tech	380±9 B	68.1±1.5 B	243±5 B	139±4 C	119±3 C

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 7. Bending values during activation of 0.016”x 0.022”, 35°C wires.

Wire	ACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 1 mm (g)	Force at 2 mm (g)	Force at 3 mm (g)
Ormco	381±19 B	68.2±3.4 B	214±11 B	241±11 A	255±11 A
AO	416±6 A	74.6±1.0 A	223±5 A	248±6 A	260±6 A
GAC	373±11 B	66.8±2.1 B	201±7 C	224±8 B	234±9 C
Org	382±8 B	68.5±1.4 B	207±7 BC	231±8 B	241±8 BC
RMO	376±11 B	67.4±2 B	207±7 BC	231±8 B	241±8 BC
Tech	380±13 B	68.1±2.3 B	208±9 BC	232±10 B	242±10 B

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Table 8. Bending values during deactivation of 0.016”x 0.022”, 35°C wires.

Wire	DEACTIVATION				
	Stiffness (g/mm)	Modulus (GPa)	Force at 3 mm (g)	Force at 2 mm (g)	Force at 1 mm (g)
Ormco	351±21 C	62.9±3.8 C	222±11 A	135±11 A	116±11 A
AO	398±7 A	71.3±1.3 A	222±5 A	133±5 A	118±5 A
GAC	351±8 D	63.0±1.5 D	199±8 C	114±9 C	98±10 C
Org	361±10 BC	64.8±1.8 BC	206±8 BC	118±8 BC	102±7 BC
RMO	359±11 BC	64.4±2.0 BC	207±8 BC	122±7 B	107±7 B
Tech	364±9 B	65.2±1.6 B	208±10 B	123±9 B	107±8 B

Different letters indicate a statistically significant ($p<0.05$) difference exists between wires for a given measure.

Figures 4-9 show representative force versus deflection curves for each of the six different brands with the four different categories of wires designated by color. As indicated by the graphs, force values for rectangular wires were larger than for the round wires consistently amongst all of the brands. Additionally, amongst the brands, it was found that the 27°C wires displayed higher force values in general than the 35°C wires within both round and rectangular wires. Figures 10-13 display the differences between the brands (as designated by color) within the four different categories of wires. The graphs show that while some brands behave more similarly to others within particular categories, there is not any one category in which all six of the brands were found to be statistically similar to one another.

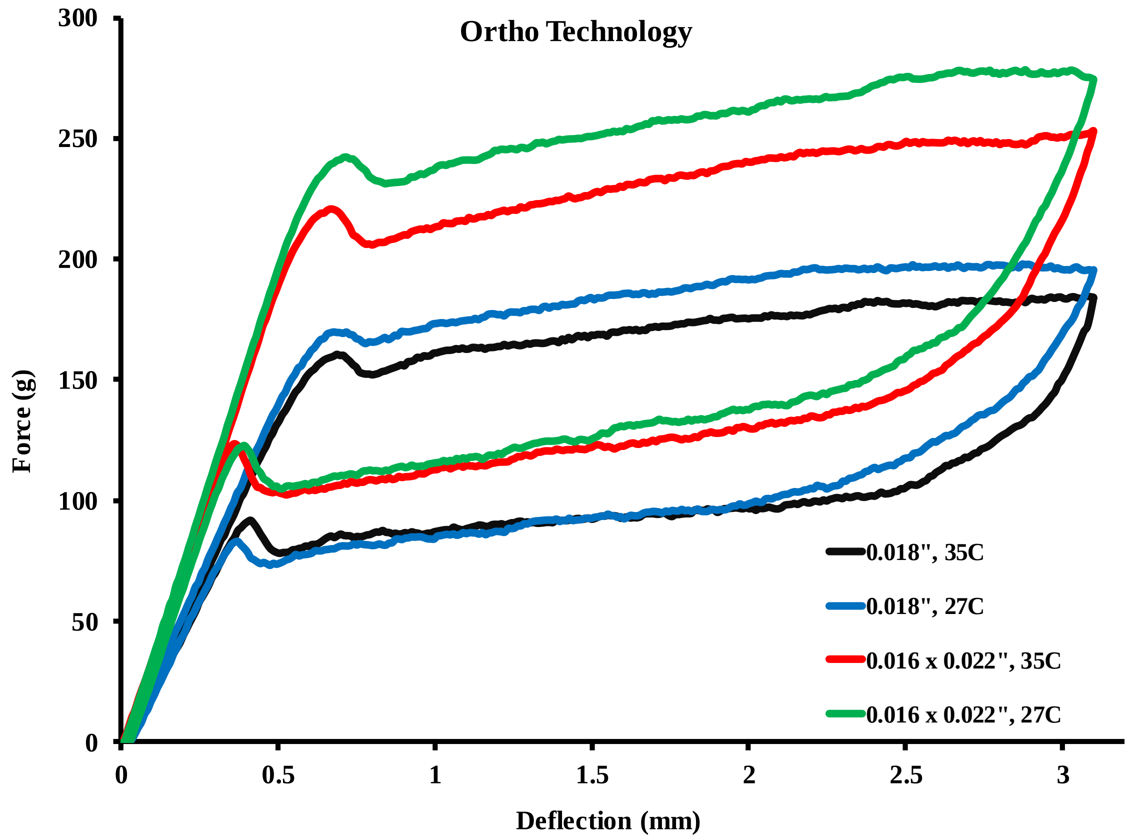

Figure 4. Force x Deflection Curve for Ortho Technology CuNiTi wires

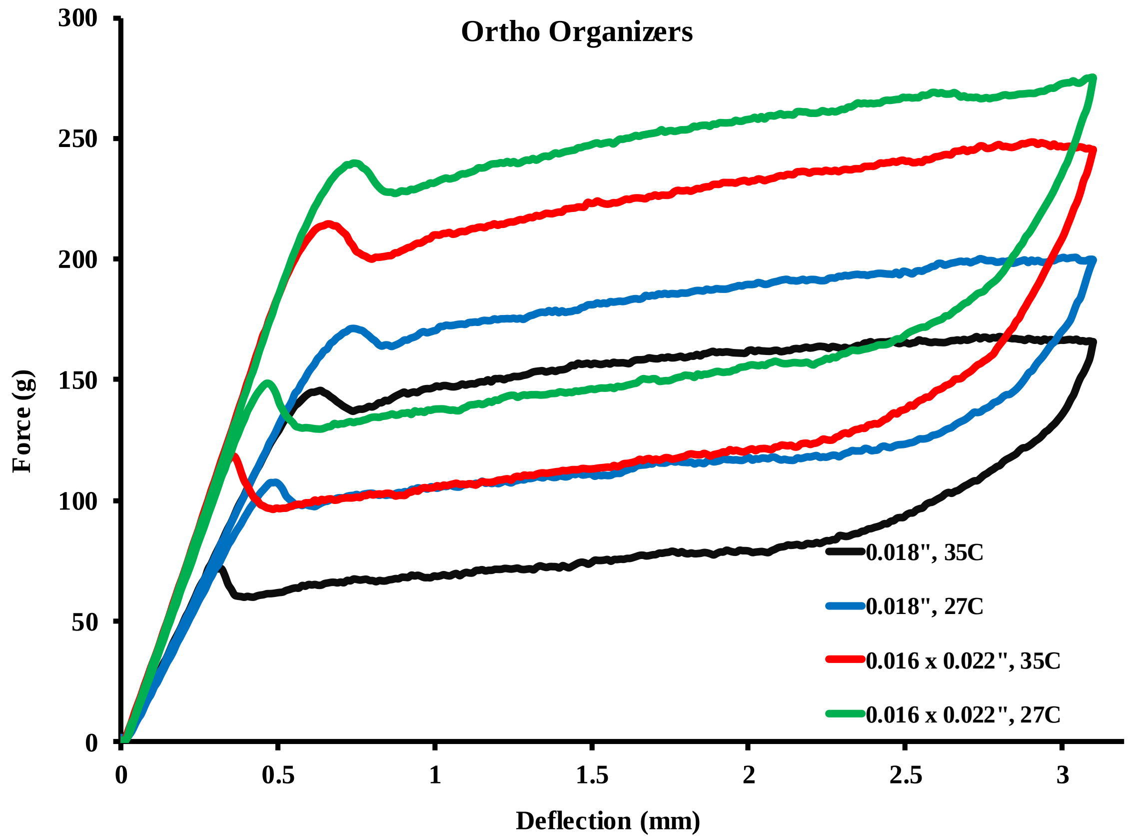

Figure 5. Force x Deflection Curve for Ortho Organizers CuNiTi wires

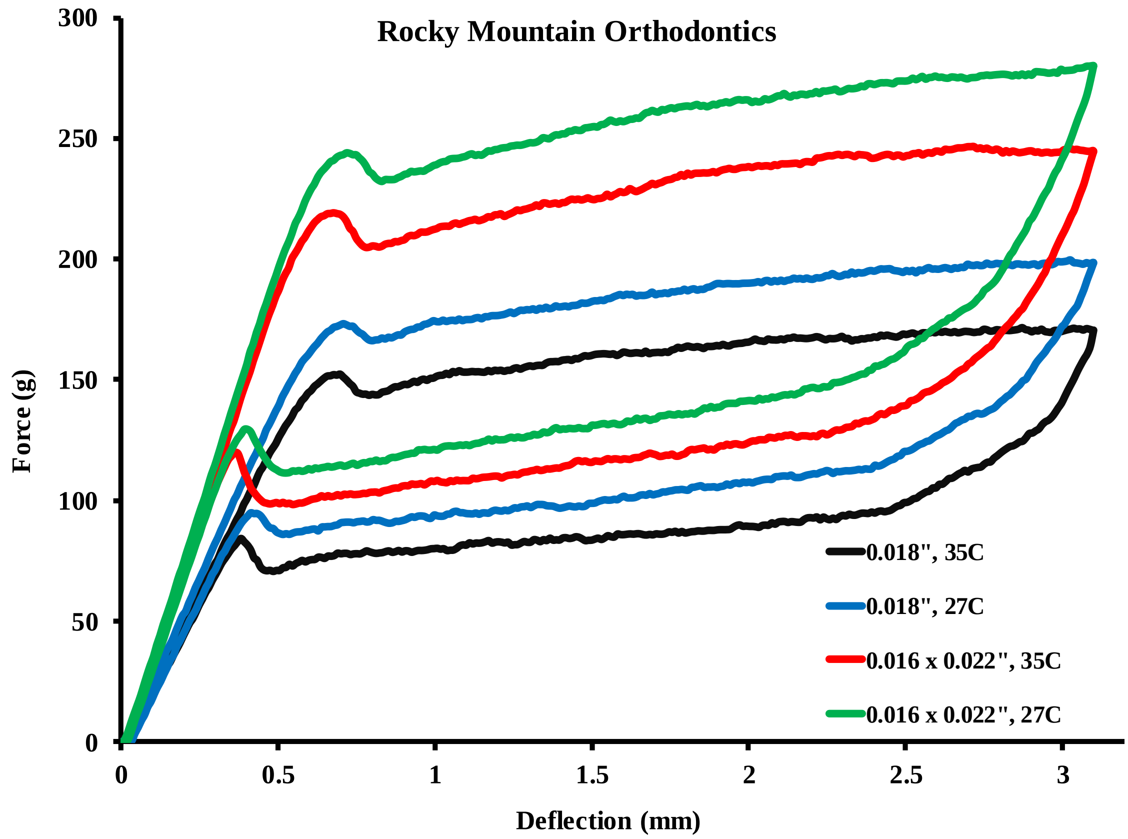

Figure 6. Force x Deflection Curve for Rocky Mountain Orthodontics CuNiTi wires

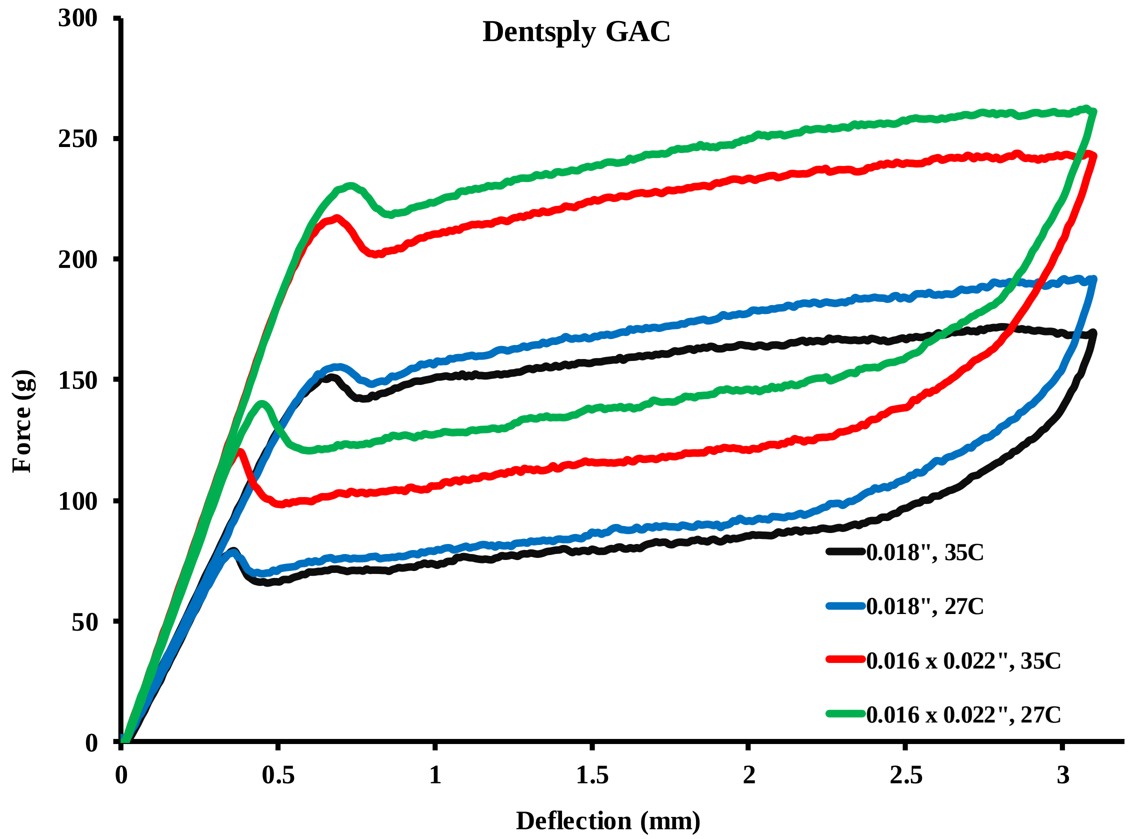

Figure 7. Force x Deflection Curve for Dentsply GAC CuNiTi wires

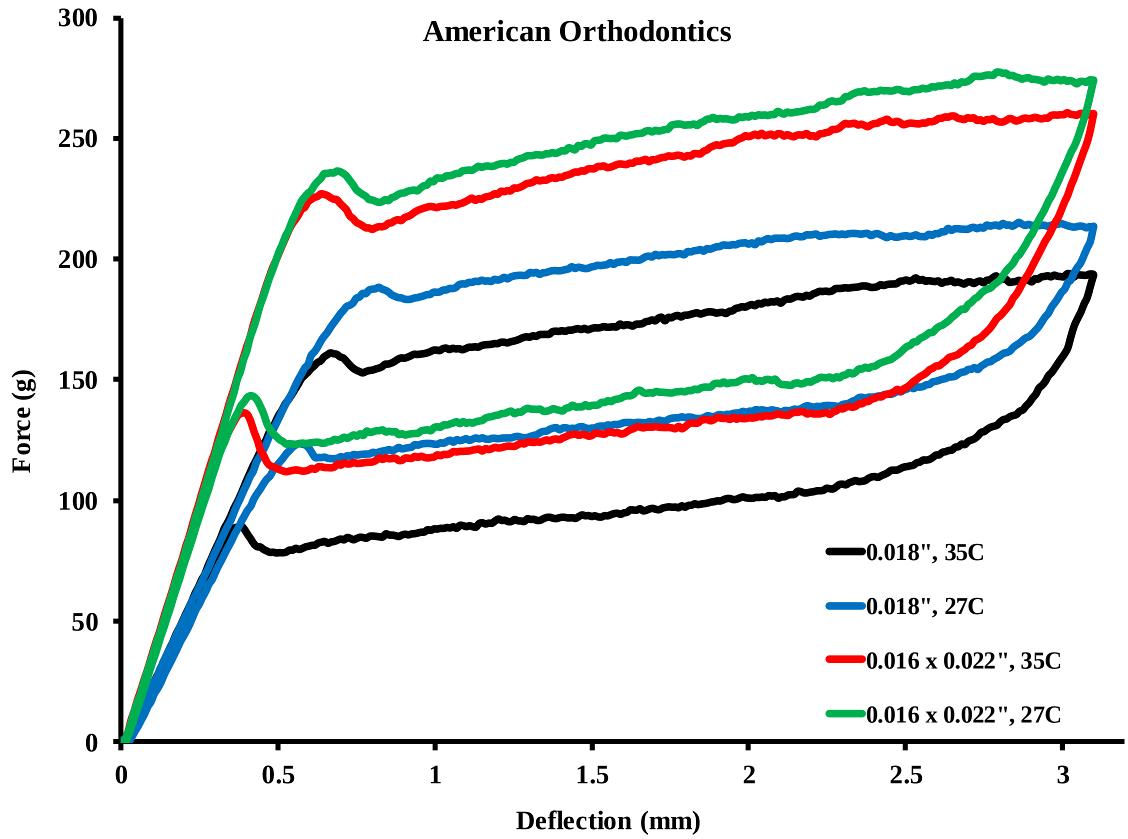

Figure 8. Force x Deflection Curve for American Orthodontics CuNiTi wires

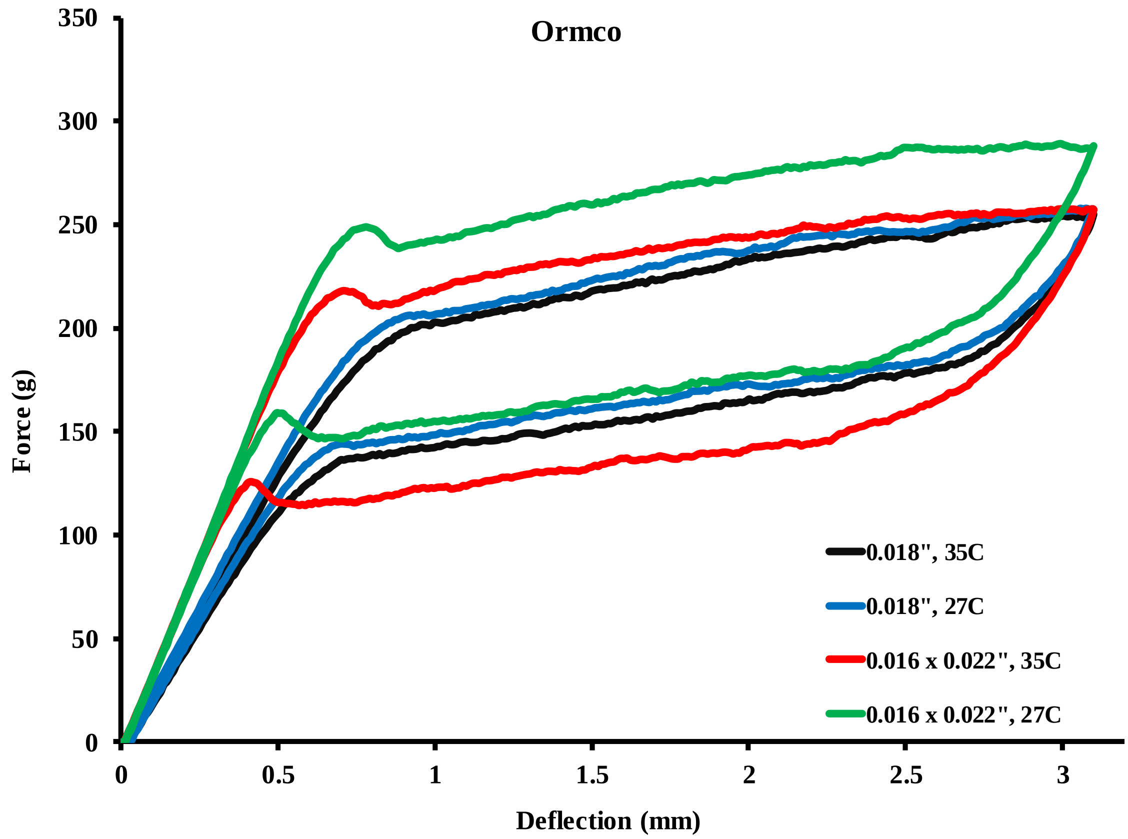

Figure 9. Force x Deflection Curve for Ormco CuNiTi wires

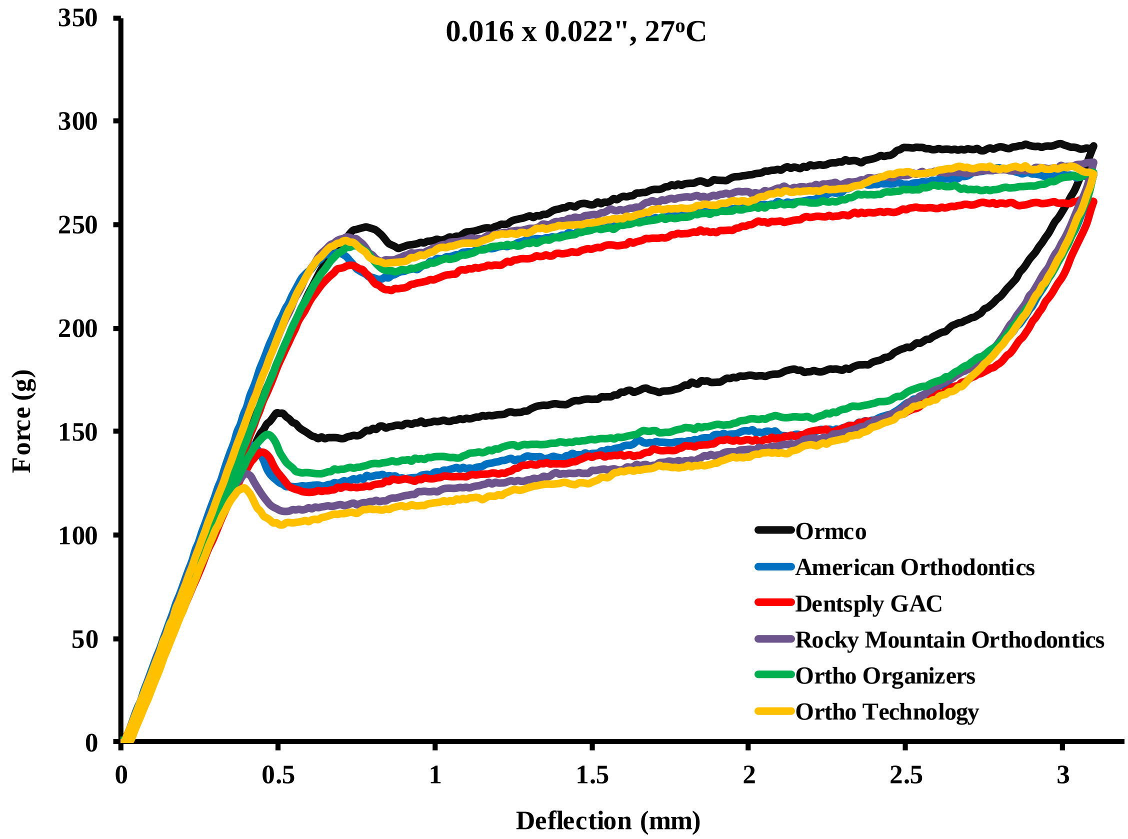

Figure 10. Force x Deflection Curve for 0.016 x 0.022”, 27ºC CuNiTi wires

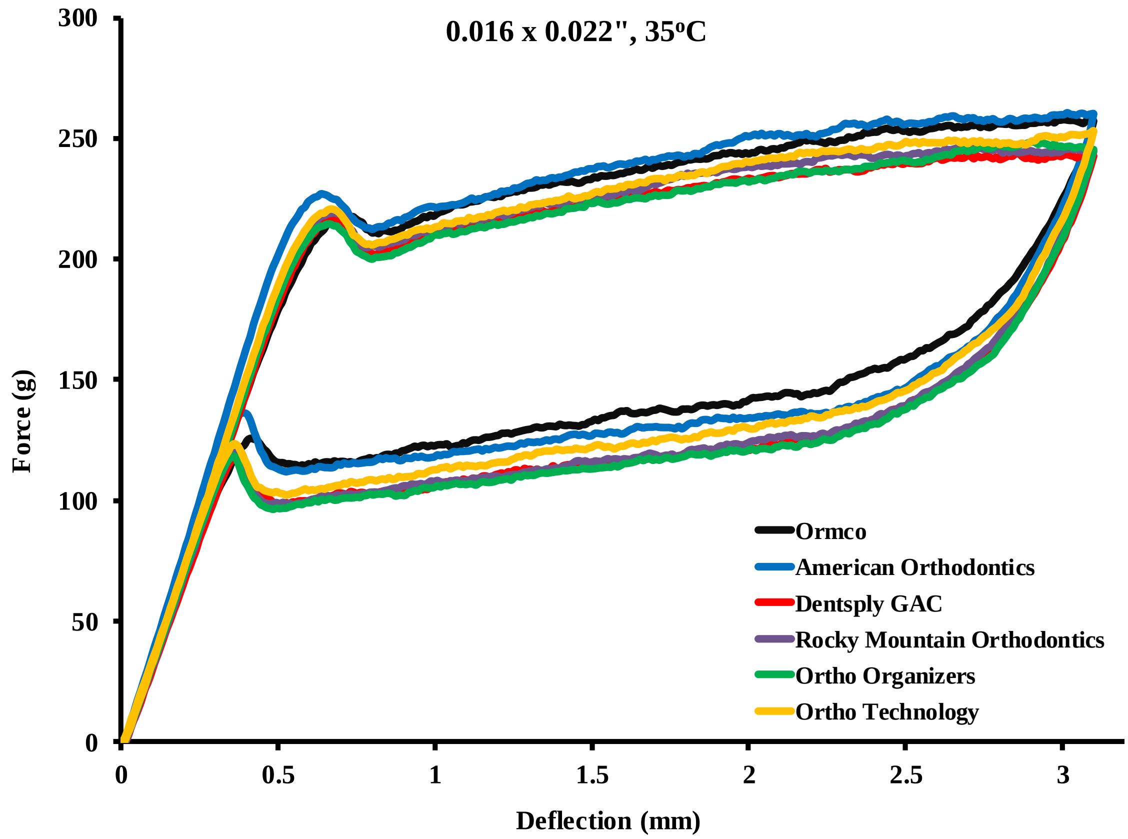

Figure 11. Force x Deflection Curve for 0.016 x 0.022", 35ºC CuNiTi wires

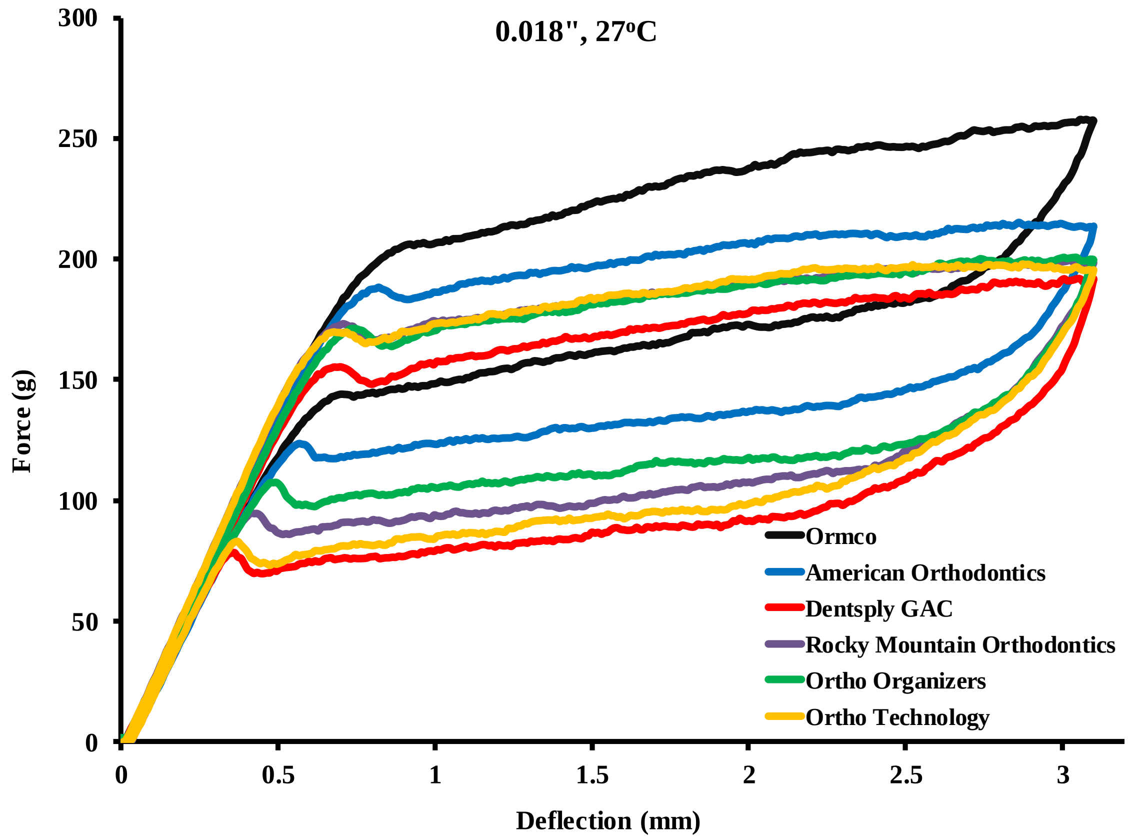

Figure 12. Force x Deflection Curve for 0.018", 27°C CuNiTi wires

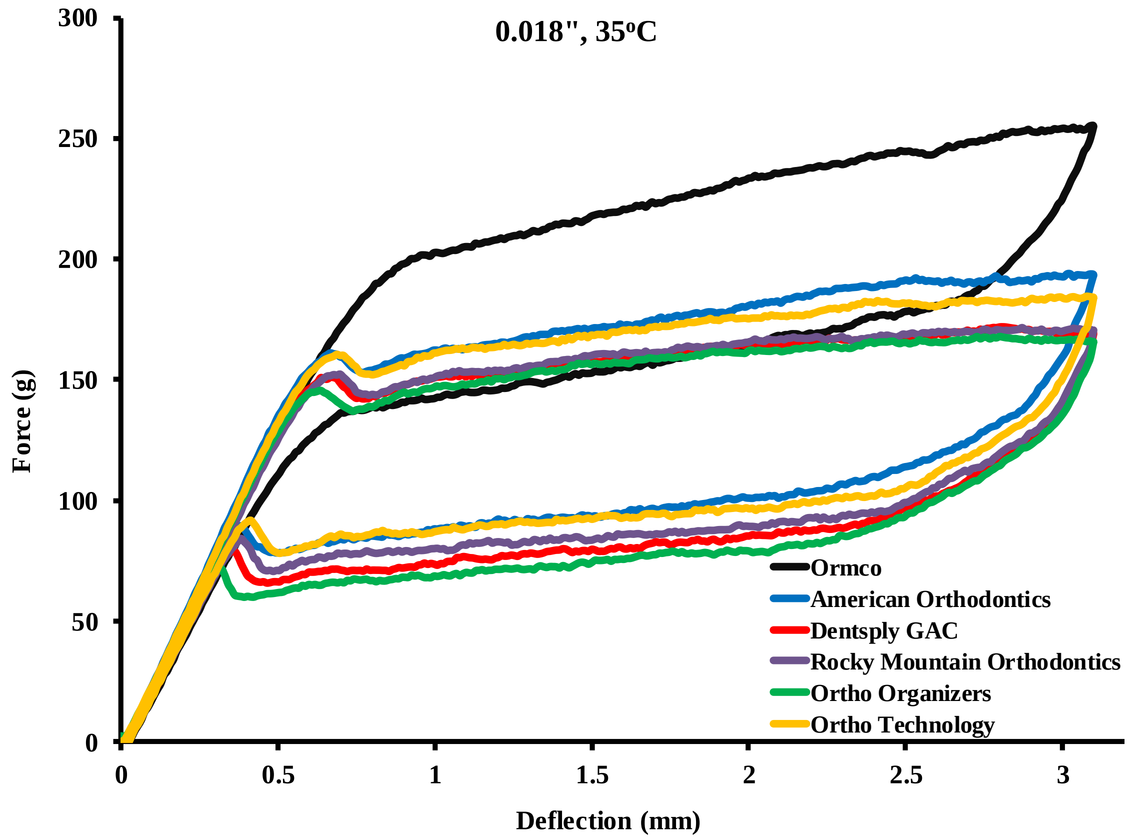

Figure 13. Force x Deflection Curve for 0.018", 35ºC CuNiTi wires

CHAPTER 5
DISCUSSION

One unique aspect of CuNiTi wires that manufacturing companies of these wires advertise is that these wires have been engineered to have a specific Af temperature, implying a significant correlation between a tightly controlled Af and a specific force delivery. In theory, this would allow the orthodontist to select a CuNiTi wire of one dimension but with varying degrees of force based on its particular Af. For example, the 27˚C Af wire would be partly austenite at room temperature (average, 22˚C) and fully austenitic at most oral temperatures (average, 36˚C) and, therefore, would provide the maximum force delivery. The 35˚C Af wire, on the other hand, would be martensitic at room temperature but only partially to totally austenitic at oral temperatures (Pompei-Reynolds and Kanavakis, 2014). These properties have been found to be consistent with the current results. Despite the brand, shape, or size of the wire tested, results consistently indicated that the 27˚C Af wires displayed higher force values than the 35˚C Af transition temperature wires.

Although the testing utilized wires from the same lots, other studies have tested orthodontic wires of the same material, dimension, and manufacturer, but from different production lots. These studies found that various manufacturing variables including heat treatment, amount of cold working, Ni:Ti ratio, etc. have been found to alter transition temperatures amongst the same types of wires from different lots. Thus, clinicians should be aware that copper-nickel-titanium archwires might not always deliver the expected force, even when they come from the same manufacturer, because interlot variations in the performance of the material exist (Fariabi et al., 1989; Pompei-Reynolds and

Kanavakis, 2014; Thompson, 2000). Since the current results showed significant differences amongst the brands even within the same temperature and shape category, it is suggestive of the possibility of different manufacturing variables amongst the various brands themselves.

Examination of Figures 4-9 show that qualitatively, Ormco's wires did not display as wide of a range of force values amongst the four wires tested compared to most of the other manufacturers' wires. This is surprising considering that Ormco was the first company to produce these wires and has done so for decades. Further, they market the wires as possessing different deactivation forces according to the different advertised transition temperatures. Thus, an orthodontist may not expect as much force difference between their 27 and 35°C wires compared to some of the other brands.

Although the results did support the presence of different force values for different transition temperatures between wires, this study was an in vitro study and thus did not ascertain the performance of the wires in a clinical situation. There have been limited in vivo studies completed to study the differences in these wires. Dalstra and Melsen completed a study to examine whether the transition temperature of copper-nickel titanium archwires has an effect on tooth movement during the initial alignment phase of orthodontic treatment. The study used a split-mouth design on fifteen randomly selected patients with identical levels of irregularity. Copper-nickel-titanium archwires were inserted. The archwires had two separate halves with two different transition temperatures: 27˚C and 40˚C. They found that the transition temperature of copper-nickel-titanium archwires does have an effect on the amount of tooth movement during alignment, however, the differences are so small that it is questionable whether they can be noticed clinically or not (Dalstra and Melsen, 2004).

Furthermore, Biermann et al. (2007) performed a study comparing as-received copper-nickel-titanium archwires to those used in patients by means of differential scanning calorimetry. They found that the clinical use of copper-nickel-titanium wires resulted in few differences when compared with as-received wires analyzed by differential scanning calorimetry.

Pandis et al. (2009) performed a study in order to compare copper-nickel-titanium vs nickel-titanium archwires in resolving crowding of the mandibular anterior dentition. Sixty patients were bonded with the same brackets and randomly split into either the copper-nickel-titanium archwire group or the nickel-titanium archwire group. The results of the study showed that the type of wire (copper-nickel-titanium or nickel-titanium) had no significant effect on crowding alleviation (Pandis et al., 2009). Therefore, it seems that the difference in loading pattern of wires in laboratory and clinical conditions might effectively eliminate the laboratory-derived advantage of copper-nickel-titanium wires. A test set up similar to this, but which would test different copper-nickel-titanium archwires would be valuable to determine if similar results would be obtained in vivo as compared to the results obtained in vitro with the three-point bend test.

Further testing to determine the clinical performance of these wires would prove beneficial to practicing orthodontists. Previous testing completed by Moore et al. (1999), found that temperatures at sites on an archwire in situ vary considerably over a 24-hour period and that racial differences do exist. Further testing of copper-nickel-titanium archwires in vivo at different sites in the mouth as well as amongst different racial groups should be considered (Moore et al., 1999). If clinically significant differences in these wires' properties exist, this should be considered during the manufacturing process and clinical use of temperature-sensitive copper-nickel-titanium archwires.

Several factors influence the final transition temperatures of a wire including the initial proportion of metals in the alloy ingot, the annealing conditions, the amount of cold work done, and the amount of time and temperature at which the wire is heat treated (Bradley et al., 1996). Small variations in these factors can yield large differences on the phase transformation temperatures. Thus, the manufacturing process appears to be sensitive, which raises the question as to whether a clinician can reasonably expect various manufacturers to provide archwires with consistent force-delivery properties.

CHAPTER 6
CONCLUSION

Wires of the same materials, dimensions, and transition temperature, but from different manufacturers do not always have the same mechanical properties. There are significant differences in activation and deactivation forces among the different manufacturers of CuNiTi archwires. Improvements should be made in the standardization of the manufacturing process of copper-nickel-titanium archwires in order to provide orthodontists with CuNiTi archwires that have consistent mechanical properties despite the manufacturing brand that produces them.

REFERENCES

American Dental Association Council on Scientific Affairs. American National Standard/American Dental Association Specification No. 32 for Orthodontic Wires. ADA Council on Scientific Affairs; 2000.

Barnes R. Determination of body temperature by infrared emission. Journal of Applied Physiology 1967: 22;1143-1146.

Biermann MC, Berzins DW, Bradley TG. Thermal analysis of as-received and clinically retrieved copper-nickel-titanium orthodontic archwires. The Angle Orthodontist 2005: 77(3): 499-503.

Bradley TG, Brantley WA, Culbertson BM. Differential scanning calorimetry (DSC) analyses of superelastic and nonsuperelastic nickel-titanium orthodontic wires. American Journal of Orthodontic and Dentofacial Orthopedics 1996:109;589-97.

Brantley WA, Eliades T, Orthodontic wires. Orthodontic Materials: Scientific and Clinical Aspects. 2001:77-103.

Boehm R. Thermal environment of teeth during open-mouth respiration. Journal of Dental Research 1972;51;75-78.

Burstone C, Qin B, Morton J. Chinese NiTi wire-a new orthodontic alloy. American Journal of Orthodontics 1985:87:445-452.

Cooper KH, Abrams RM. Attributes of the oral cavity as a site for basal body temperature measurements. Journal of Obstetric, Gynecologic, and Neonatal Nursing 1984:13;125-129.

Dalstra M, Melsen B. Does the transition temperature of Cu-NiTi archwires affect the amount of tooth movement during alignment? Orthodontics and Craniofacial Research 2004:7;21-25.

Fariabi S, Thoma PE, Abujudom DN. The effect of cold work and heat treatment on the phase transformations of near equiatomic NiTi shape memory alloy. Proceedings of the International Conference of Martensitic Transformations. 1989.

Fernandes DJ, Peres RV, Mendes AM, Elias CN. Understanding the Shape-Memory Alloys Used in Orthodontics. International Scholarly Research Notices Dentistry 2011:132408.

Gil FJ, Planell JA. Effect of Copper addition on the superelastic behavior of Ni-Ti shape memory alloys for orthodontic applications. J Biomed Mater Res (Applied Biomaterials) 1999:48;682-8

International Organization for Standardization – ISO. ISO 15841:2014: dentistry: wires for use in orthodontics. Geneva:ISO; 2014

Kusy RP. A review of contemporary archwires: their properties and characteristics. The Angle Orthodontist 1997:67;197-208.

Kusy RP. Orthodontic biomaterials: from the past to the present. The Angle Orthodontist 2002:72; 501-512.

Longman C, Pearson G. Variations in tooth surface temperature in the oral cavity during fluid intake. Biomaterials 1987:8;411-414

Mairiaux P, Sagot JC, Candas V. Oral temperature as an index of core temperature during heat transients. Eur J Appl Physiol Occup Physiol 1983:50; 331-41.

Meeran NA. Biological response at the cellular level within the periodontal ligament on application of orthodontic force – an update. Journal of Orthodontic Science. 2012: 1(1);2-10

Michailesco P, Marcianio J, Grieve A, Abadie M. An in vivo recording of variations in oral temperature during meals: a pilot study. Journal of Prosthetic Dentistry 1995:73;214-218

Miura F, Mogi M, Ohura Y, Hamanaka H. The superelastic property of the Japanese NiTi alloy wire for use in orthodontics. American Journal of Orthodontics and Dentofacial Orthopedics 1986:90:1-10.

Moore R, Watts J, Hood, J, Burritt D. Intra-oral temperature variation over 24 hours. European Journal of Orthodontics 21 1999:249-261.

Nikolai RJ. Orthodontic wire: A continuing evolution. Seminars in Orthodontics. 1997: 3;157-165.

Pandis N, Polychronopoulou A, Eliades, T. Alleviation of mandibular anterior crowding with copper-nickel-titanium vs nickel-titanium wires: a double-blind randomized control trial. American Journal of Dentofacial Orthopedics. 2009: 136(2);152

Pompei-Reynolds E, Kanavakis G. Interlot variations of transition temperature range and force delivery in copper-nickel-titanium orthodontic wires. American Journal of Orthodontics 2014:146 (2); 215–226

Proffit WR, Fields HW, Sarver DM, Ackerman JL. Journal of Contemporary Orthodontics. 5th ed. St. Louis, MO: Mosby, 2013.

Reitan K. Some factors determining the evaluation of forces in orthodontics. American Journal of Orthodontics. 1957:43;32-45.

Sachdeva RCL, Miyazaki S, Farzin-Nia F. Orthodontic archwire and method of moving teeth. U.S. Patent 5,044,947, September 3, 1991.

Santoro M, Nicolay OF, Cangialosi TJ. Pseudoelasticity and thermoelasticity of nickel-titanium alloys: a clinically oriented review. Part 1: Temperature transitional ranges. American Journal of Orthodontics and Dentofacial Orthopedics 2001:119:587-93.

Sloan R, Keatinge W. Depression of sublingual temperature by cold saliva. British Medical Journal 1975:1;718-720.

Storey E. The nature of tooth movement. American Journal of Orthodontics. 1973:63;292-314.

Terndrup T, Allegra J, Kealy J. A comparison of oral, rectal, and tympanic membrane-derived temperature changes after ingestion of liquids and smoking. American Journal of Emergency Medicine 1989: 7;150-154

Thompson SA. An overview of nickel-titanium alloys used in dentistry. International Endodontics Journal. 2000:33;297-310.

Volchansky A, Cleaton-Jones P. Variations in oral temperature. Journal of Oral Rehabilitation 1994:21;605-611

Zehner W, Terndrup T. The impact of moderate ambient temperature variance on the relationship between oral, rectal, and tympanic membrane temperatures. Journal of Clinical Pediatrics 1991: 30;61-64