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How does temperature influence the properties of rectangular nickel–titanium wires?

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SUMMARY Thermodynamic nickel–titanium (NiTi) wires have become increasingly popular. The relationship between the temperature variation within the mouth and the force level delivered is, however, far from elucidated. The aim of this study was to evaluate the influence of possible intraoral temperature differences on the forces exerted by seven commercially available 0.019 × 0.025 inch NiTi archwires. As mouth temperature ranges from 33 to 37°C most of the time, all wires were tested at five different temperatures between 30 and 40°C in an orthodontic wire-testing device, a so-called Force System Identification (FSI) apparatus, placed in a climate chamber. In the FSI a two-bracket system using self-ligating Damon brackets simulated first order displacements up to 4 mm. At each temperature five samples of each archwire brand were tested. The following variables from the activation/deactivation curves were calculated: force and displacement at the yield point, maximum force level, total energy up to maximum displacement, energy loss after deactivation, force and displacement at the beginning and at the finish of the plateau, and the slope of the plateau. Any statistically significant differences in these variables for the different brands and temperature levels were analysed using one-way analysis of variance.

The results showed that: (1) The behaviour of all wires was different. (2) Copper NiTi40 showed the lowest and the most constant force level, followed by NeoSentalloy 200 g. On the other hand, these wires may not work properly in mouth breathers as no forces were exerted below 35°C. (3) If the use of superelastic characteristics and low force levels are the reasons for utilizing rectangular NiTi wires, austenitic NiTi wires should be avoided.

Introduction

Nickel–titanium (NiTi) wires are widely used within orthodontics as they combine shape memory effect and superelasticity with excellent corrosion and mechanical properties, and good biocompatibility.

Shape memory is desirable, as the return to its original austenitic phase from a pronounced plastic deformation of the same wire in its martensitic phase allows for a long range of activation. The superelasticity is likewise related to the internal transformation, the consequence of which is the release of a constant force over a considerable part of the deactivation. This has been illustrated by a load-deflection plot with a horizontal plateau during unloading, which implies that a constant force may be exerted over a long range of tooth movement (Burstone *et al.*, 1985; Miura *et al.*, 1986). The transformation of austenite into martensite can be either induced by cooling or produced by stress. Martensite formation can be initiated by cooling the material below M_s (defined as the temperature at which martensitic transformations begins). M_f is the temperature at which martensitic transformation ends. The transformation is reversible, and A_s is the temperature at which the reverse austenitic transformation (martensite → austenite) begins upon heating, and A_f is the temperature at the end of the reverse austenitic transformation. When stress is applied to the material above its A_f temperature, an elastic martensitic phase is stress-induced in alloys that exhibit thermoelastic behaviour (Barwart, 1996). The stress necessary to induce the formation of stress-induced martensite (SIM) is a linear function of temperature. When the applied stress is released below A_s, the shape change produced remains, because reverse rearrangements of twins and martensite variants have not occurred. However, on heating through the A_s-to-A_f temperature range, the material regains its original shape by a reverse transformation from martensite to austenite. Thus, the original shape is re-established and the deformation of the martensitic phase recovered (shape memory effect).

Early martensitic superelastic NiTi wires exhibited shape memory characteristics, but their transitional temperature range (TTR) made it impractical to exploit this property for orthodontic treatment. Burstone *et al.* (1985) and Miura *et al.* (1986) introduced austenitic NiTi, which presented superelastic characteristics. More recently, third and fourth generation temperature-dependent heat activated (also called thermoresponsive or thermodynamic) NiTi wires have been marketed with clinical useful shape memory.

The evaluation of the physical properties has been ascertained either by cantilever tests (Burstone *et al.*, 1985; Khier *et al.*, 1991), or three-point bending (Miura *et al.*, 1986; Yoneyama *et al.*, 1993; Tonner and Waters, 1994; Ibe and Segner, 1998; Nakano *et al.*, 1999; Iijima *et al.*, 2002; Wilkinson *et al.*, 2002; Fischer-Brandies *et al.*, 2003; Parvizi and Rock, 2003). Three-point bending tests offer reproducibility, which has facilitated comparison between studies. However, none of these methods simulate the clinical situation. This is the reason why the three-bracket method was introduced (Oltjen *et al.*, 1997). In spite of many attempts, the ideal test cannot be performed, since the clinical efficiency depends not only on force systems and surface related variables, but also the delivery of the force and the functional environment into which the wire is inserted. It has been suggested that the most appropriate wire test may be that which reproduces conditions encountered clinically, where the wire is constrained as part of a fixed appliance. Oltjen *et al.* (1997) demonstrated significant differences between the three-point bending test and the three-bracket bending mode, and similar findings were found by Parvizi and Rock (2003).

The physical properties of the new thermodynamic NiTi wires have made it possible to insert larger guage rectangular wires during the initial phases of orthodontic treatment in order to gain three-dimensional control of tooth movement. Although many studies have focused on the evaluation of NiTi wires (Table 1), large guage rectangular wires have not yet been submitted to any laboratory tests, leaving clinicians to rely only on the manufacturer's information.

Variation in mouth temperature throughout a 24-hour period has been studied in several ways, but the median cluster is around 35°C with variation occurring over time (Moore *et al.*, 1999) and within the different locations of the mouth (Volchansky and Cleaton-Jones, 1994; Airoldi *et al.*, 1997). The reported range was generally large, up to 50°C, although the peak values were only reached for very short periods and mostly in the palatal zone. The majority of the time (79 per cent), mouth temperature ranged between 33 and 37°C. Most studies were performed at 37°C while others were carried out at 35°C (Table 1). The influence of changes in force delivery within the

Table 1 NiTi wire-testing studies that expressed the temperature in which the tests were performed.

Reference	Testing mode	Temperature (°C)	Cross-sections of wire (inches)	NiTi type / manufacturer
Burstone *et al.* (1985)	Cantilever configuration	22, 37, 60	Ø0.016	Martensitic (M-NiTi), Austenitic (A-NiTi) / Ormco, 3M Unitek
Khier *et al.* (1991)	Cantilever configuration	22	Ø0.016, Ø0.018, 0.018 × 0.025, 0.021 × 0.025	M-NiTi, A-NiTi / 3M Unitek, GAC, Lancer, Rocky Mountain
Miura *et al.* (1986)	Three-point bending test	37	Ø0.014, Ø0.016, Ø0.018, Ø0.020, Ø0.022	M-NiTi, A-NiTi / 3M Unitek, Tomy Inc.
Yoneyama *et al.* (1993)	Three-point bending test	37	Ø0.039	Not reported
Tonner and Waters (1994)	Three-point bending test	5, 15, 20, 25, 30, 35, 40, 50	Ø0.014, Ø0.016, Ø0.018	M-NiTi, A-NiTi / GAC, Orthocare, Forestadent, Dentaurum, Russell and Baker, Masel, Orthomax, 3M Unitek, American Orthodontics, Ormco, Lancer
Ibe and Segner (1998)	Three-point bending test	35	0.016 × 0.022	Thermodynamic, A-NiTi / GAC, Forestadent, Masel, Imperial Precise
Nakano *et al.* (1999)	Three-point bending test	37	Ø0.016, 0.016 × 0.022	Thermodynamic, M-NiTi, A-NiTi / A-Company, Hoya, Lancer, Sankin, Ormco, Rocky Mountain, GAC, TP, 3M Unitek
Fischer-Brandies *et al.* (2002)	Three-point bending test	22, 37, 60	0.016 × 0.022	Thermodynamic, M-NiTi, A-NiTi / GAC, Ormco, Dentaurum, Forestadent, Lancer
Iijima *et al.* (2002)	Three-point bending test	23, 37, 60	0.016 × 0.022	Thermodynamic, A-NiTi / Ormco, Tomy Inc.
Wilkinson *et al.* (2002)	Three-point bending test, orthodontic brackets	22, 35.5, 44	Ø0.016	A-NiTi, Thermodynamic / GAC, Ormco, TP, Dentaurum, 3M Unitek
Parvizi and Rock (2003)	Three-point bending test, phantom head test	20, 30, 40	Ø0.016, 0.016 × 0.022	A-NiTi, Thermodynamic / 3M Unitek, Direct Ortho, Ortho Care
Santoro and Beshers (2000)	Three-bracket bending tests	4 to 60 in steps of 3	Ø0.018, 0.016 × 0.022, 0.017 × 0.025	Thermodynamic / GAC, Ormco, 3M Unitek
Gurgel *et al.* (2001)	Three-bracket bending tests	35	0.017 × 0.025	Thermodynamic, A-NiTi / Ormco, Masel, Morelli, 3M Unitek, GAC, Dentaurum, TP
Filleul *et al.* (1997)	Torsion	37	0.017 × 0.025, 0.018 × 0.025	Thermodynamic, A-NiTi / Ormco, GAC
Meling and Ødegaard (1998)	Torsion	18, 27, 37, 40	0.016 × 0.022, 0.017 × 0.025, 0.018 × 0.025	Thermodynamic, M-NiTi, A-NiTi, Multi-stranded / Dentaurum, Forestadent, GAC, Highland Metals, Masel, Ormco, 3M Unitek
Gurgel *et al.* (2001)	Torsion	35	0.017 × 0.025	Thermodynamic, A-NiTi / Ormco, Masel, Morelli, 3M Unitek, GAC, Dentaurum, TP

above-mentioned range has not yet been described in detail.

It was, therefore, the aim of the present study to evaluate the influence of possible intraoral temperature differences on the forces exerted by seven commercially available 0.019 × 0.025 inch NiTi archwires.

Materials and methods

The seven NiTi wires analysed in this study and their respective codes are shown in Table 2. All wires were tested in an orthodontic wire-testing device, the Force System Identification (FSI) apparatus, which was developed at the Department of Orthodontics, School of Dentistry, University of Aarhus, Denmark. The wire was clamped into two wire holders, in which mechanical sensors are placed. The moments and forces generated between the wire and the holders are transformed into electrical impulses by means of specially developed strain gauges. Six step motors control the translation and rotation of the two holders in three planes of space. The displacements of the holders are computer controlled, and input for these is supplied by the user. The moments and forces developed are stored in the computer, together with the positions of the holders, for further statistical analysis. The error of the method for this system has been evaluated (Menghi *et al.*, 1999).

A self-ligating Damon bracket for the upper first premolar (Ormco Corp., Glendora, California, USA) was fixed in the centre of both holders of the FSI system (Figure 1). Initially, the two brackets, fixed on the two holders, were placed in alignment to each other at a distance of 5 mm. The tested wires comprised 15 mm long pieces of straight wire inserted passively into the two aligned brackets. During testing, the brackets were displaced in translation, in steps of 0.2 mm up to 4 mm and back to the aligned position again. This simulated Class I geometry in an aligning phase (first order movements). Forces and moments were recorded corresponding to each step. The force systems developed in the first order are reported here. Five wires of each batch were tested at five different temperatures.

The tests were performed inside a climate chamber (Department. of Environmental Medicine, University of Aarhus) with a precision of 0.3°C at the following temperatures: 30, 33, 35, 37 and 40°C. The wires were kept inside the climate chamber with the stabilized temperature for at least two hours prior to testing.

Before statistical evaluation of the data was carried out, corrections were made to the raw data for differences between the locations where the forces and moments were measured and the centre of the brackets. The activation/deactivation curve of the NiTi wires is characterized by three distinct phases reflecting the transformation between austenite and martensite. In order to compare the curves characterizing the different wires and the influence of the different temperatures, a number of variables were determined.

Figure 2 illustrates a typical force and moment curve in which the above-mentioned variables and their definitions are shown.

The means and standard deviations were calculated for all variables for each set of measurements. The intra-batch variation was evaluated, as was the influence of temperature for each batch. The different products were compared both with respect to intra-batch variation as average behaviour. The behaviour of each wire in the different tested temperatures (intra-wire) and of different wires in the same temperature (inter-wire) were compared using one-way analysis of variance, followed by the Student–Newman–Keuls *post-hoc* test.

Results

The temperature dependency of the individual wires is illustrated in Figure 3. Regardless of the force level, the Formo-Elastic Wonder Wire (WWFE) demonstrated the smallest range (635–699 cN) in the force delivered during the transition between the temperatures of 30 and 40°C. The normal NiTi (ON) revealed the most pronounced temperature dependency, augmenting the force delivery from 216 to 465 cN when the temperature increased.

Graphs of the unloading curves of the seven wires at the five temperatures are shown in Figure 4. Although all tested wires had the same dimensions, three different groups could be distinguished when the tests were performed at 30 and 33°C. At 35, 37 and 40°C four different behaviours could be observed by visual inspection.

Table 2 Overview of the seven commercially available NiTi wires used in the present study.

Code	Wire brand	Manufacturer	Type
C35	35°C Thermo-Active Copper NiTi®	Ormco Corp. (Glendora, CA, USA)	Thermodynamic
C40	40°C Thermo-Active Copper NiTi®	Ormco Corp.	Thermodynamic
G&H	Thermal NiTi	G&H Wire Comp. (Greenwood, IN, USA)	Thermodynamic
NS200	NeoSentalloy 200g	GAC Intl. (Central Islip, NY, USA)	Thermodynamic
ON	NiTi	Ormco Corp.	Austenitic
WWFE	Formo-Elastic™ NiTi	Wonder Wire Corp. (Wyomissing, PA, USA)	Austenitic
WWT	Thermal NiTi	Wonder Wire Corp.	Thermodynamic

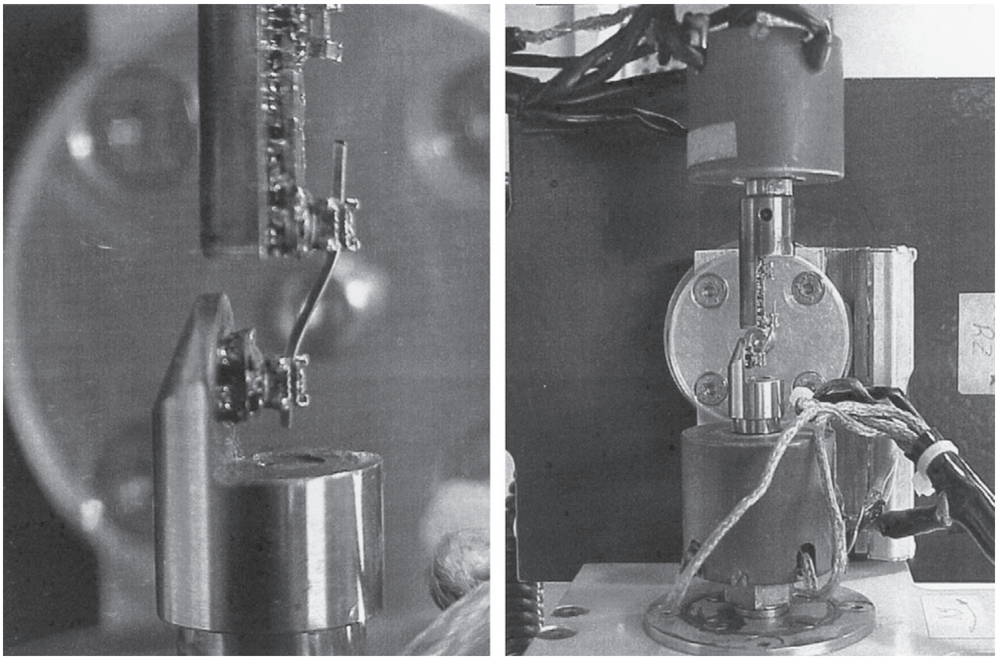

Figure 1 Force System Identification apparatus with two self-ligating Damon brackets testing the wire in first order activation.

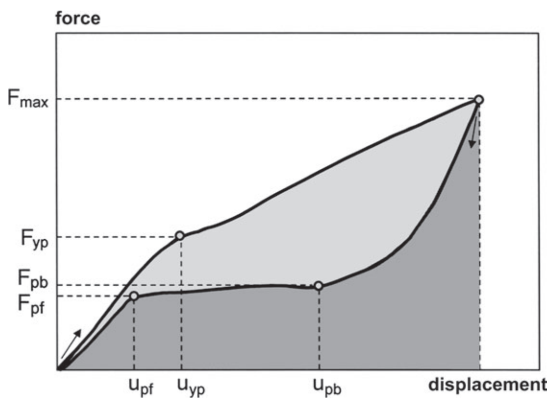

Figure 2 Variables used in this study indicated in a typical force/displacement curve. Force (F_{yp}) and displacement (u_{yp}) of the yield point (defined as the end point of the initial linear slope), maximum force level (F_{max}), total energy (E_{tot}) up to maximum displacement, energy loss (in percentage of total energy) after deactivation, force (F_{pb}) and displacement (u_{pb}) at the beginning of the plateau, force (F_{pf}) and displacement (u_{pf}) at the finish of the plateau, slope (s_p) of the plateau.

The yield points (Table 3) had a tendency to be higher with increasing temperature for almost all wires. The WWFE was the only wire which did not show this behaviour. The Copper NiTi40 (C40) and NeoSentalloy200 (NS200) wires had the lowest yield points. The force level at the yield point also had a tendency to increase with temperature in all wires. Again C40 and NS200 wires were those with the lowest force values. The highest values were observed for WWFE.

Table 4 presents data concerning the unloading plateau. As observed for the yield point values, the force values increased with temperature for all wires. The inter-wire comparison showed the lowest force levels for the C40 and NS200 wires. The plateau length had a tendency to decrease when the temperature increased. The inter-wire ranking (plateau length) differed within each temperature. The lowest values were observed for the WWFE followed by the ON. The lowest plateau slope value was exhibited by the 35°C thermo-active Copper NiTi wire (C35).

Discussion

This study made use of a new methodology for testing seven different brands of NiTi wires. Despite the difficulties that this poses when comparing the present findings with previous studies, the methodology could be expected to better simulate a clinical situation (Oltjen *et al.*, 1997; Parvizi and Rock, 2003). If the three-point bending test had been applied, the friction between bracket and wire would not have been taken into consideration. The tested wires had a dimension of 0.019 × 0.025 inches sliding in 0.022 × 0.028 inch slots, which is a common clinical situation.

The use of large guage rectangular NiTi wires in the initial phase of orthodontic treatment is supported by the idea that it is possible to generate low force levels due to material properties and also to have three-dimensional control of the tooth movement from the beginning of treatment. Nevertheless, few studies have tested such rectangular NiTi wires.

Meling and Ødegaard (1998) claimed that it was not possible to observe superelastic behaviour when different wires were tested in torsion up to 25 degrees. Despite the

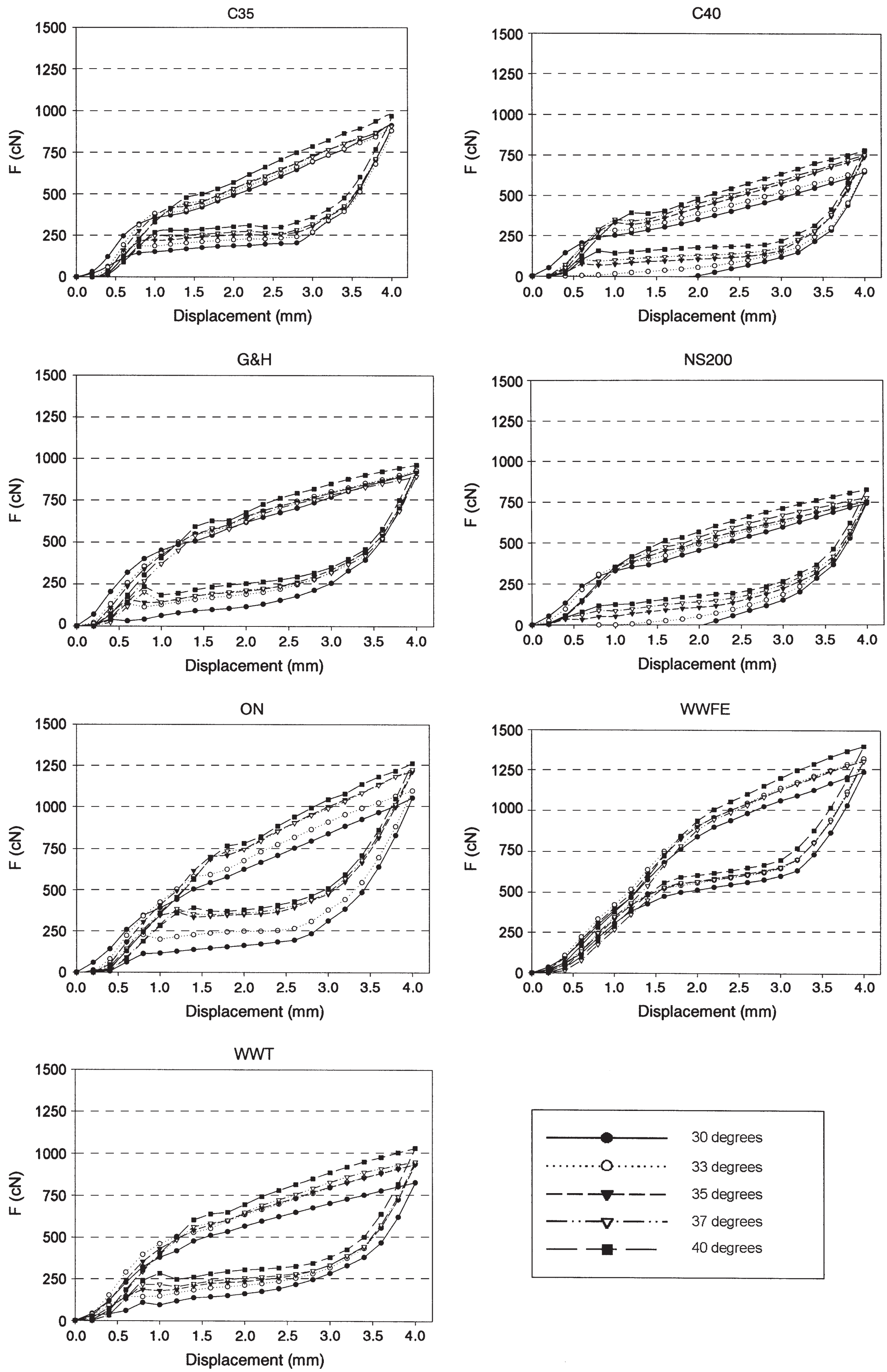

Figure 3 Temperature-dependency of the seven different brands of archwires. (See Table 2 for definitions of abbreviations.)

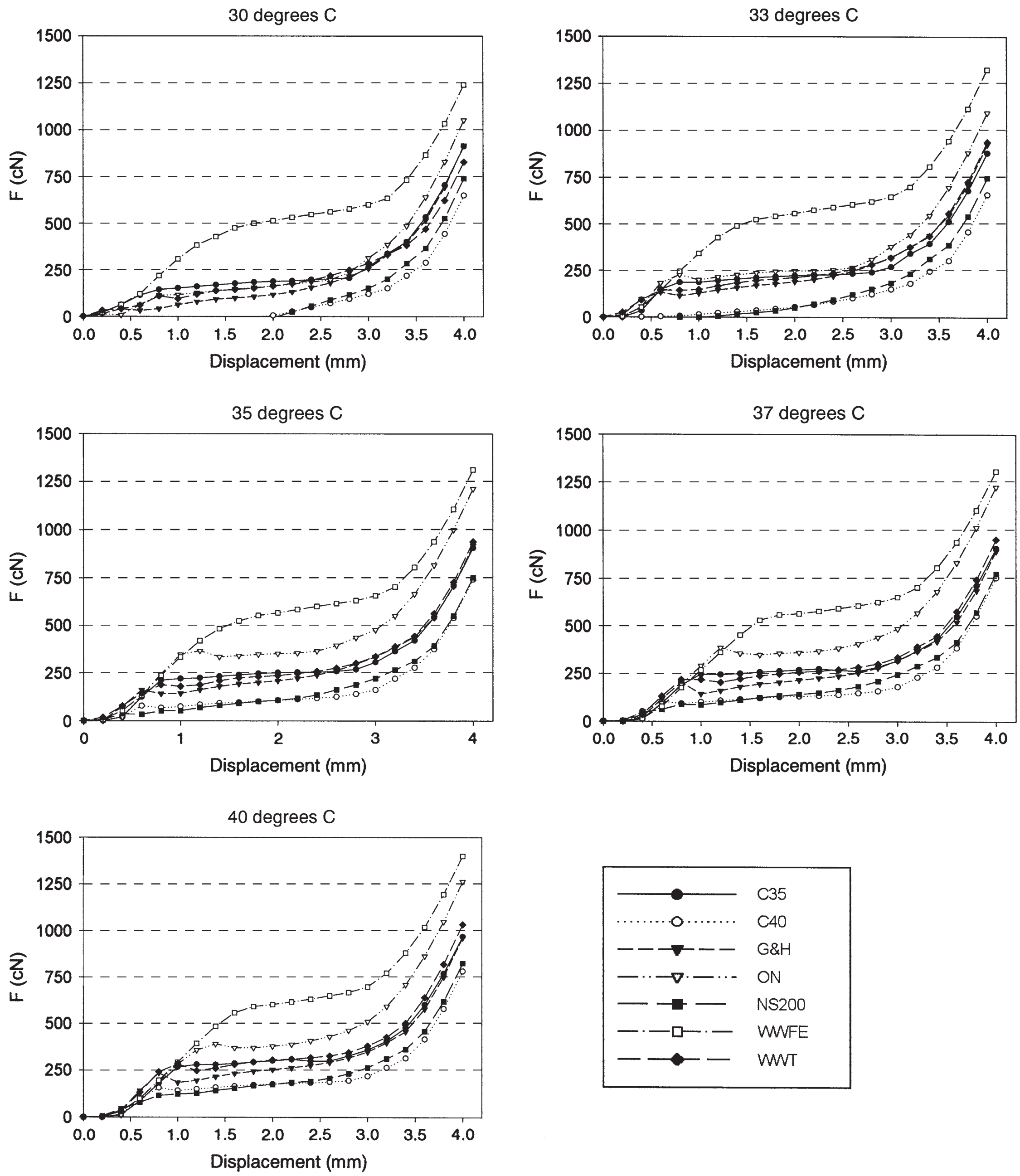

Figure 4 Unloading curves of the tested archwires at the five different temperatures. (See Table 2 for definitions of abbreviations.)

fact that they tested thermodynamic NiTi wires, they failed to show the unloading plateaus. This finding cannot be evaluated in this study, as only forces and bending moments, developed in the first order when two adjacent teeth were mutually displaced, were assessed. The bending moments are not reported, as they can be deduced directly from the forces and the inter-bracket distance.

The temperatures in which the tests were performed were chosen in order to simulate the oral environment. It has been previously demonstrated that cold/hot intakes are very transient (Airoldi *et al.*, 1997). Temperatures of 30 and 33°C can simulate the oral environment of a mouth breather. Volchansky and Cleaton-Jones (1994) demonstrated temperatures below 32°C after 10 minutes of the mouth being open. In a study by Moore *et al.* (1999), the median temperature in the incisor area was recorded as 33°C for some individuals. The temperatures most frequently utilised in the testing of wires are 35 and 37°C, as they represent the normal temperature for nasal breathers (Volchansky and Cleaton-Jones, 1994; Airoldi *et al.*, 1997: Moore *et al.*, 1999). The temperature of 40°C simulates a patient with fever and is also noted as the A_f of C40 wire.

Table 3 The yield point and energy loss variables of the tested NiTi wires with the intra-wire (inter-temperature) rankings (A: lowest; E: highest) and the inter-wire rankings (I: lowest; VII: highest). Variables with the same ranking are not significantly different.

Wire*	Temp (°C)	Displacement at yield point (mm)				Force at yield point (cN)				Energy loss (percentage)			
		Mean	SD	Ranking		Mean	SD	Ranking		Mean	SD	Ranking	
				Intra	Inter			Intra	Inter			Intra	Inter
C35	30	0.8	0.0	A	II	319	13	A	II,III	51	1	E	II
	33	1.0	0.0	B	II	383	4	B	II	47	1	D	II
	35	1.2	0.0	C	II	417	5	C	II	45	1	C	III
	37	1.2	0.1	C	II	414	18	C	II	43	1	B	III
	40	1.4	0.0	D	III	479	4	D	II	41	1	A	III
C40	30	0.6	0.1	A	I	207	25	A	I	79	2	E	V
	33	0.8	0.0	B	I	285	5	B	I	70	2	D	VI
	35	1.0	0.0	C	I	334	6	C	I	62	1	C	VI
	37	1.0	0.0	C	I	352	6	D	I	59	1	B	VI
	40	1.2	0.0	D	II	394	5	E	I	53	1	A	VI
G&H	30	0.9	0.2	A	II	439	37	A	IV	65	2	D	IV
	33	1.3	0.1	B	III	535	24	B	IV	56	1	C	V
	35	1.4	0.1	B	III	547	20	B	IV	54	2	B	V
	37	1.5	0.1	B	IV	572	21	B	III	53	1	B	V
	40	1.5	0.1	B	III	618	15	C	III	51	1	A	V
NS200	30	0.8	0.0	A	II	298	3	A	II	81	1	E	VI
	33	0.8	0.0	A	I	307	8	A	I	72	0	D	VII
	35	1.0	0.1	B	I	344	15	B	I	63	0	C	VII
	37	1.2	0.0	C	II	404	21	C	II	60	0	B	VI
	40	1.1	0.1	B	I	383	30	C	I	56	0	A	VII
ON	30	0.8	0.0	A	II	346	15	A	III	58	1	C	III
	33	1.4	0.0	B	III	581	30	B	V	50	1	B	III
	35	1.6	0.0	C	IV	703	8	C	V	41	0	A	II
	37	1.7	0.1	D	V	722	29	C	IV	39	1	A	II
	40	1.8	0.1	D	IV	767	36	D	IV	39	2	A	II
WWFE	30	2.1	0.1	B	III	867	32	A	V	33	0	C	I
	33	1.9	0.1	A	IV	885	23	A,B	VI	32	1	B	I
	35	2.0	0.0	A,B	V	904	14	A,B	VI	31	0	A	I
	37	2.1	0.1	B	VI	923	37	B	V	31	0	A	I
	40	2.1	0.1	B	V	984	23	C	V	30	1	A	I
WWT	30	0.9	0.1	A	II	359	37	A	III	58	2	D	III
	33	1.0	0.1	A	II	465	29	B	III	54	1	C	IV
	35	1.1	0.1	A	I	459	45	B	III	51	1	B	IV
	37	1.4	0.0	B	III	564	20	C	III	50	1	B	IV
	40	1.4	0.1	B	III	619	12	D	III	47	1	A	IV

*See Table 2 for definitions of abbreviations.
SD, standard deviation.

The yield point differed between the different wires and varied according to temperature (Table 3). The superelastic behaviour of the WWFE wire was only present when the distance between the brackets was greater than 2 mm. If the activation was lower than 2 mm, the force level could reach higher values than when it was activated to a level greater than the yield point. According to Proffit and Fields (1993), some austenitic NiTi wires exhibit stiffness higher than that of TMA® wires, if the deformation does not reach that of the proportional limit. The clinician can best make use of the superelastic properties if the wire has a low yield point. In this study C40 and NS200 wires presented the lowest yield points followed by C35 and Thermal NiTi (WWT). When the force levels at the yield points were compared, C40 wire showed the lowest force levels at all the different temperatures.

The energy loss presented in Table 3 represents the hysteresis of each wire, that can be explained as the difference between the loading and unloading curves of one test. The high values of C40 and NS200 suggest that the metallic structure was not in only one phase, especially at the lowest temperatures tested. According to Filleul *et al.* (1997), the C40 wire should start the transformation from martensite to austenite at 24.5°C and finish at 40°C. The same values for the C35 wire are 14.2 and 36.3°C. From the austenitic NiTi wires tested, the ON wire showed a 19 per cent difference in energy loss between 30 and 40°C, which was considerably higher than the WWFE (3 per cent). It can

Table 4 The unloading plateau variables of the tested NiTi wires with the intra-wire (inter-temperature) rankings (A: lowest; D: highest) and the inter-wire rankings (I: lowest; VII: highest). Variables with the same ranking are non-significantly different.

Wire*	Temp(°C)	Force at start (cN)					Plateau length (mm)				Plateau slope (cN/mm)			
		At mm	Mean	SD	Ranking		Mean	SD	Ranking		Mean	SD	Ranking	
					Intra	Inter			Intra	Inter			Intra	Inter
C35	30	2.80	206	6	A	III	2.0	0.1	C	V	31.8	4.3	B	I
	33	2.92	254	18	B	II,III	2.2	0.1	D	III	33.3	4.3	B	I
	35	2.80	268	8	B	II	2.0	0.0	C	II	28.5	4.9	A,B	I,II
	37	2.80	285	4	C	II,III	1.8	0.0	B	III	21.3	3.4	A	I
	40	2.60	301	13	D	II	1.6	0.0	A	II	20.6	8.0	A	I
C40	30	3.20	151	13	A	I	1.3	0.1	A	II	119.3	9.6	D	V
	33	3.20	182	8	B	I	2.6	0.3	C	IV	71.0	7.0	C	III
	35	3.04	168	20	A,B	I	2.4	0.1	C	III	36.7	7.1	B	II
	37	3.00	181	6	B	I	2.4	0.0	C	V	32.1	5.5	A,B	I,II
	40	2.88	207	20	C	I	2.1	0.1	B	IV	23.5	10.4	A	I
G&H	30	2.60	180	16	A	II	2.2	0.0	B	VI	63.8	5.9	B	III
	33	2.56	242	16	B	II	2.0	0.1	A	II,III	54.4	6.1	A,B	II
	35	2.60	263	19	C	II	2.0	0.1	A	II	53.4	10.1	A,B	III
	37	2.72	269	11	C	II	2.0	0.0	A	IV	48.1	16.7	A,B	II,III
	40	2.80	318	11	D	II	2.0	0.0	A	IV	41.1	1.8	A	II
NS200	30	3.00	151	2	A	I	1.0	0.0	A	I	157.9	6.3	C	VI
	33	3.00	185	7	B	I	2.0	0.0	C	II,III	92.7	3.7	B	IV
	35	2.52	149	11	A	I	2.1	0.1	C	II	53.2	4.2	A	III
	37	2.56	178	11	B	I	2.0	0.2	C	IV	54	8.0	A	III
	40	2.56	206	7	C	I	1.8	0.1	B	III	50.5	4.4	A	II
ON	30	2.72	216	19	A	III	1.9	0.1	B	IV	50.4	5.6	B	II
	33	2.64	272	22	B	III,IV	1.9	0.2	B	II	30.8	14.0	A	I
	35	2.48	374	11	C	IV	1.5	0.1	A	I	17.9	9.9	A	I
	37	2.76	435	22	D	IV	1.6	0.1	A	II	30.7	14.0	A	I,II
	40	2.80	465	37	D	IV	1.6	0.1	A	II	53.2	5.2	B	II
WWFE	30	3.20	635	3	A	V	1.6	0.1	B	III	97.5	4.1	A	IV
	33	3.04	655	21	A	V	1.5	0.1	A,B	I	91.0	6.4	A	IV
	35	3.04	665	28	A	V	1.4	0.2	A	I	92.3	11.0	A	IV
	37	3.04	659	31	A	V	1.4	0.0	A,B	I	86.0	14.2	A	IV
	40	3.00	699	21	B	V	1.3	0.1	A	I	89.0	16.7	A	III
WWT	30	3.20	333	10	C	IV	2.4	0.0	C	VII	93.6	8.5	C	IV
	33	2.80	284	11	A	IV	2.2	0.1	B	III	59.3	11.4	B	II
	35	2.80	301	4	B	III	2.1	0.1	A,B	II	59.8	9.9	B	III
	37	2.80	302	14	B	III	2.0	0.0	A	IV	42.0	3.2	A	II,III
	40	2.84	352	11	D	III	2.0	0.0	A	IV	45.6	6.1	A	II

*See Table 2 for definitions of abbreviations.
SD, standard deviation.

be suggested that the TTR of the ON wire was closer to mouth temperature than the WWFE and that this fact explains the different behaviours between the two wires. Bradley *et al.* (1996) demonstrated the A_s for the ON wire as −13°C and the A_f as 40°C, while Filleul *et al.* (1997) found 19.8°C and 29°C using differential scanning calorimetry measurements. The energy loss seems to be inversely proportional to the amount of force at the yield point.

Observation of the graphic representation revealed that, in all cases, the largest energy loss occurred at the very start of unloading, whereafter a plateau representing the transition occurred.

The forces delivered during unloading, representing the forces acting on the teeth, are shown in Figure 4. The graph comparing the different wires tested at 30°C shows the C40 and NS200 wires without unloading plateaus. This suggests that both wires were not in an austenitic phase, meaning that 30°C is probably below the A_f for these wires. Extrapolating this finding to a clinical situation, it can be suggested that these two wires should not be used in mouth breathers, where anterior tooth alignment is required. In this case the lowest force level would be given by the Thermal NiTi (G&H) wire. The same comments apply to the findings at 33°C (Figure 4).

When studying the variation in intraoral temperature, Moore *et al.* (1999) found that for the majority of the time the upper central incisor and the first premolar areas are in the range of 35–36°C and are above 37°C for only 1 per cent of the time. The fact that the C40 and NS200 wires did not deliver any or only low forces below 37°C, indicates that the forces were delivered intermittently and, in addition, at the lowest level. Nevertheless, Dalstra and Melsen (2004) revealed, in a comparison of Copper NiTi 27°C and 40°C, where patients were advised to drink hot liquids or mouthwash with hot water, that the rate of tooth movement was superior when the C40 wire was used. The efficiency of the low force level and the intermittent force corroborates the findings in orthopaedic research when studying the effect of loading on bone turn-over (Rubin *et al.*, 1996) The efficacy of the low force was further confirmed by Damon (1998) who repeatedly demonstrated the rapid levelling which occurred when inserting a 35°C Copper NiTi. The rationale behind the application of low forces is further supported by the paradigm regarding the tissue reaction to low and heavy forces suggested by Melsen (1999). This was recently reinforced by Cattaneo (2003) in a finite element analysis carried out on human material.

The C40 wire (Figure 4 and Table 4) had a flatter plateau (lower slope) than the NS200 wire, although both presented very similar characteristics when tested at 35°C. The force levels were half that of the second group composed of G&H, WWT and C35 wires.

The tests performed at 37°C and 40°C showed similar results as those at 35°C.

When the wires were compared at 35°C and 37°C, the C40 wire presented the longest plateau length with a very small slope. The C35 wire showed the flattest plateau (constant force) of all the wires, but the force level was higher than that for C40, NS200, G&H and WWT.

All wires showed characteristic graphs in all tested temperatures (Figure 3). They may have come from the same factories, but the different graphs show that they do not have the same behaviour. WWFE wire demonstrated the smallest property differences within the 10-degree temperature range used in this investigation. On the other hand, ON wire showed the largest differences. Despite the fact that these two wires were the austenitic NiTi wires tested in the present study, they showed both extremes of behaviour. The common observation for these two wires is that they showed the highest force delivery.

Conclusions

Based on the present findings of 0.019 × 0.025 inch NiTi wires it seems valid to conclude that:

1. All wires demonstrated different behaviours and were differently influenced by the variation in temperature, showing that the force delivery variation is the norm for the studied NiTi wires.
2. Copper NiTi 40°C showed the lowest and the most constant force level followed by NeoSentalloy 200 g. On the other hand, these wires would not work correctly in mouth breathers as no forces were exerted below 35°C.
3. If superelastic characteristics and low force levels are the reasons for utilizing rectangular NiTi wires, the use of austenitic NiTi wires, such as the normal NiTi and the Formo-Elastic, should be avoided.

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