Comparisons of the thermodynamic properties of three nickel-titanium orthodontic archwires

This manuscript is dedicated to the memory of Dr. George Andreasen, whose inquisitive mind made it possible for our profession to benefit from his innovations.

Samir E. Bishara, DDS, BDS, D.Ortho, MS; John M. Winterbottom, BS, MS; Abdel-Hak A. Sulieman, BDS, MS, PhD; Kwan Rim, B.Eng, PhD; Jane R. Jakobsen, BA, MS

Nitinol was first alloyed in the early 1960s by William Buehler at the U.S. Naval Ordnance Laboratory in Silver Springs, Maryland. Its name was built from the elements which comprise the alloy and the place where it was first produced: *ni* for nickel, *ti* for titanium, and *nol* for Naval Ordnance Laboratory.[1,2] This alloy can be drawn into two forms of wire—superelastic nitinol and thermodynamic nitinol—each with unique properties.[3]

Superelastic nitinol archwires were introduced to clinical orthodontics by Dr. George Andreasen in 1972.[4] The development of nitinol archwires represented a significant advance in orthodontic biomechanics and treatment. Compared with stainless steel archwires, nitinol wires exert light continuous forces when deflected relatively large distances, with minimal permanent deformation. Superelastic nitinol has other advantages, including a significant reduction in the number of archwire changes needed to align and level teeth.[5]

Dr. Andreasen also tested thermodynamic nitinol wires in the 1980s,[6] although they were introduced commercially for clinical use in orthodontics only in the last few years. Essentially, these wires can return to a previously set shape when heated to their transition temperature range (TTR). Andreasen first suggested that shape changes in nitinol wires might be used to apply forces to the teeth in order to move them

Abstract

The unique memory property of thermodynamic wire is only partially understood. It is believed to result from the wire's inherent capability to markedly alter its atomic bonding forces as a function of temperature. This shape recovery phenomenon may be the result of a transition in crystal structure that occurs by deformation and cooling. When the transition is reversed, by heating, the structure reverts to its original form and abrupt property changes occur. The purpose of this study was to determine the transition temperature ranges (TTR) of three commercially available thermodynamic archwires and to determine the rate of recovery of the wires when bent to a uniform shape.

A jig was constructed to hold the wires and was suspended in a water bath within a plexiglass box. The temperature of the water bath was gradually increased. A program was written to acquire a single video frame from a running video tape and then allow the operator to graphically overlay the position of each wire specimen.

The results indicate that the TTRs for the three commercially available thermodynamic wires are of similar magnitudes ($\bar{x}$ = 6.7° C, 6.2° C and 6.7° C). The greatest differences were in the standard deviations (1.3° C, 2.2° C and 3.7° C) which may be a function of manufacturing during alloying of the wire and/or its heat treatment.

Key Words

Thermodynamic archwires • Nitinol • Recovery • TTR

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Table 1
Details on the various archwires used in the study

Materials	Manufacturer	Size	Type
1. Active Arch Nitinol	3M Unitek Monrovia, Calif.	.017 x .025	Upper
2. Heat Activated Nitinol	Ortho Arch Co., Inc. Hoffman Estates, Ill.	.017 x .025	Upper
3. Neo Sentalloy	GAC International, Inc. Central Islip, NY	.018 x .025	Upper

orthodontically. A thermodynamic nitinol archwire can be completely engaged in the brackets of malpositioned teeth and when heat inside the mouth raises the wire through its TTR, the wire will begin to regain its original shape. As a result of these changes, orthodontic forces are applied to the teeth.[2]

To get the wire to "memorize " a certain form, it must first be set into the desired shape and held tightly while undergoing a high temperature heat treatment.[6] After the wire is cooled to room temperature it can easily be deformed below the TTR because the nitinol alloy is highly ductile.[1] When the wire is then heated above the TTR, the alloy will return to its original shape.[7] TTRs can be obtained from well below room temperature up to 275°F or higher.[2] The specific TTR is a function of the composition of the alloy as well as its processing history.[2] One way the TTR can be altered is by varying the nickel content of the alloy or substituting cobalt for part of the nickel.

The unique memory property of thermodynamic wire is only partially understood, but it is believed to result from the alloy's inherent capability to alter its atomic bonding forces as a function of temperature.[1] This shape recovery phenomenon is the result of a transition in crystal structure (atomic and electron shifts) that occurs by deformation and cooling. Upon reversing the transition by heating, the structure reverts to its higher temperature form, accompanied by abrupt changes in properties.[2] Amazingly, this is a reversible process.

An ideal thermodynamic nitinol wire would have the following characteristics:[5-9] 1) dead soft at room temperature so that it can be tied easily, 2) instantaneously activated by the heat of the mouth, 3) able to apply clinically acceptable orthodontic forces that would result in tooth movement, 4) once fully activated, would not be affected further by increased heat in the mouth, and 5) a fairly narrow TTR, i.e., it should be completely active at mouth temperatures yet completely passive at lower temperatures. This property would allow the clinician sufficient time to tie the archwire into the bracket slots before the heat of the mouth activates the wire.

At this point, a definition of terms is in order. The shape-memory effect can be regarded as a combination of two effects: thermoelasticity and pseudoelasticity.[10] The thermoelastic martensitic transformation is continuous as the temperature is lowered and is not accompanied by the sudden appearance of groups of platelets.[10] Kousbroek[11] defined the shape memory effect as a "phenomenon by which, after an apparent plastic deformation, a metal alloy upon heating starts to remember its original shape at a certain temperature and return to its deformed shape upon cooling." Pseudoelasticity, on the other hand, was defined as "the effect by which a material recovers the induced plastic strain upon loading." With pseudoelasticity, temperature remains constant. It has been suggested that thermoelastic and pseudoelastic effects are complimentary, i.e., if one effect is small the other will be large and vice versa, with a 100% total recovery for polycrystals above the start of the thermoelastic martensitic transformation.[11]

Forces transmitted by thermodynamic wires

Andreasen first reported the use of a .019" thermodynamic wire with a TTR between 30 and 45°C. When the wire was activated by the heat of the oral cavity, it moved crowded mandibular incisors into alignment in 163 days. The .019" thermodynamic nitinol archwire exerted forces comparable to a .012" stainless steel archwire.[6]

Langwith[12] demonstrated that a .021" x .025" thermodynamic nitinol archwire with a TTR that approximates body temperature (35 to 39°C) can be used as an effective leveling and retraction archwire.

In another study, Wass[13] evaluated the forces generated by activated thermodynamic nitinol wire as a function of the magnitude of deflection and the temperature change. Deflection varied between 0.5 and 2.0 mm, while the temperature varied between 90°F (32°C) at the lower limit of the TTR and 115°F (46°C) at the upper limit. The combination of these two factors generated forces that ranged between 55 and 365 gm. The latter values were at maximum deflections and highest TTR.[13] Wass suggested that the range of acti-

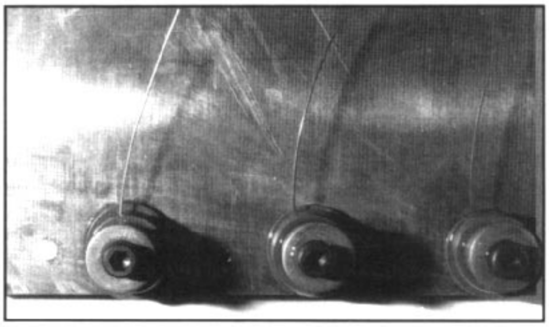

Figure 1

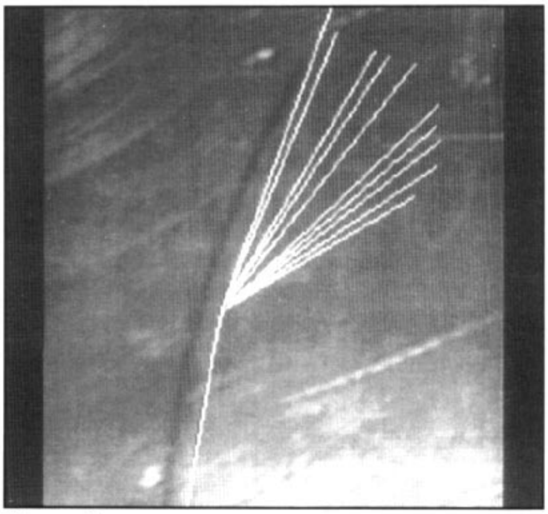

Figure 2

Figure 1
Special jig used to mount the wires to be suspended in the water bath.

Figure 2
Superimposed graphic overlays depicting the recovery of the wire.

vation, i.e., the TTR, needed to be reduced.[13]

As a result, one of the most important clinical parameters that needs to be determined is the range of TTRs in commercially available thermodynamic orthodontic archwires.

The purpose of this study was to determine the TTR of three commercially available thermodynamic archwires and to determine the rate of recovery of the wires when bent to a uniform shape.

Materials and methods

The wires: Three commercially available thermodynamic orthodontic archwires were used in this study. Detailed information on these wires is presented in Table 1.

Each archwire was cut in half and the anterior, most rounded part of the wire was discarded. Ten samples of each archwire type were tested.

The wire holder: The wires were mounted in a special jig with screws and rubber stoppers (Figure 1). Once mounted, the wires did not touch each other or the platform of the jig. After being mounted on the jig, the wires were bent uniformly using a DeLa Rosa contouring plier (Dentronix Orthodontic Instruments and Supplies, Ivyland, Pa). Such an approach was designed to avoid influencing the recovery of the wire by prematurely exposing it to body temperature through the operator's fingers. The curved pliers created a bend in the wire that ranged between 30 and 40°, without causing permanent deformation in the wire. The wires were not touched by hand once they were mounted and bent. In a pilot study on two samples of each wire type, it was determined that a bend of up to 50° did not result in a permanent deformation of the wires.

The water bath: The jig with the wires was suspended in a water bath in a plexiglass (Polymethyl Methacrylate) box (1' x 1' x 2'). The water bath was heated with a special heater (Constant Temperature Immersion Circulator, model 730, Poly Science, Niles, Ill) that increased the temperature of the water at a constant rate for the duration of the test period. The temperature of the bath was monitored with a graduated thermometer accurate to ±0.2°C. A stop watch was mounted next to the jig to monitor elapsed test time. The initial temperature of the bath ranged from 18° to 21°C, below the TTR of any of the archwires tested.

A video camera was used to record the recovery of the wires as the temperature rose. Recording continued for 5 minutes after the last noted wire motion.

Video recording: Recovery measurements were obtained from video tapes using a Macintosh IIfx computer (Apple Computer Inc., Cupertino, Calif) equipped with a Neotech Image Grabber board and IPlab version 2.1 0g software (Signal Analytics, Vienna, Va).

A program was written to acquire a single video frame from the running video tape. The operator could then graphically overlay the position of each wire specimen. The overlay was saved and another video frame acquired. The saved graphic overlays were then superimposed on the newly acquired image to see if recovery had occurred (Figure 2). If motion was noted, the overlay was modified to reflect the motion, and the angle of change was then measured.

The time and temperature at which the overlay was modified were recorded and the process continued until the change in the wire had been completed. Frames were grabbed from the running video tape approximately once every 30 seconds throughout the test. When no additional motion was observed, the overlay was "stamped" onto the image and the relative changes in angle measurements were made for the entire test.

Table 2
Descriptive statistics for the span of the temperature transition ranges (TTR) of the different wires tested

Wire Type	$\bar{x}$	S.D.	Range
Wire #1	6.7°	1.3°	5.0° - 8.5°
Wire #2	6.2°	2.2°	3.0° - 9.0°
Wire #3	6.7°	3.7°	2.0° - 14.0°

$\bar{x}$ = Mean S.D. = Standard deviations
F - Value = 0.09 P = 0.9160

Table 3
Descriptive statistics of the mean transitional temperature change for each type of wire tested

	TTR in (°C)			Magnitude of initial recovery in degrees at the lower limits of the TTR		
Type	$\bar{x}$	S.D.	Range	$\bar{x}$	S.D.	Range
Wire #1	25.2	1.8	22.4 - 28.0	2.4	1.0	1.2 - 3.4
Wire #2	24.7	1.1	23.0 - 26.5	3.4	0.7	2.4 - 4.7
Wire #3	25.3	2.7	21.0 - 28.8	3.7	1.2	2.5 - 6.1
	F Value = 0.22		P = 0.80	F Value = 4.46		P = 0.02*

$\bar{x}$ = mean S.D. = Standard Deviation
*Wire #1 had a significantly smaller angle of initial recovery than wires #2 or #3

Statistical analysis

Cross-sectional comparisons: The Analysis of Variance General Linear Models procedure was used to compare the transition temperature ranges of the three wires as well as the magnitude of the recovery at three temperature ranges, 20.0 to 25.0°C, 25.1 to 30.0°C and 30.1 to 36.0°C.

Recovery curve comparisons: The mean recovery curves associated with the temperature changes for each wire type were compared using the Analysis of Variance General Linear Models procedure. In the statistical analysis of the recovery curves, there are two aspects to be evaluated, shape or profile and magnitude. The shape or profile of the curve is the slope that describes the direction of change. In this respect, the curves may show a parallel relationship indicating that the recovery trends are the same. On the other hand, lack of parallelism among curve profiles indicates differences in these trends. The curve magnitude describes the amount of change with temperature held constant. This method of analysis was described in detail by Kleinbaum and Kupper.[14]

The level of statistical significance was predetermined at the 0.01 level of confidence for the comparisons of curve parallelism and at the 0.05 level of confidence for the comparisons of curve magnitude. This variation in the level of significance is suggested by Bonferroni. The Bonferroni method takes into consideration all tests of significance to be examined in one analysis.[15]

Results

General observations

The absolute lower TTR limit for the wire specimens tested was 22.5°C, with the upper limits not exceeding 36°C. In other words, all of the TTRs observed were at or below normal mouth temperature.

It was also noted that in four out of the nine specimens from Wire #3 (Neo Sentalloy), the wire first moved in the direction of the bend before moving in the direction of recovery.

Comparisons of the transitional temperature changes (Tables 2 and 3)

Comparisons of the TTRs of the three wire types (Table 2) indicated that there were no significant differences in the range of temperatures from initial recovery to complete recovery. The largest range was associated with wire #3.

Comparisons of the angle of initial recovery (Table 3)

The comparisons indicated that the magnitude of initial recovery was significantly different between the three wire types ($P = 0.02$). Wire #1 showed a significantly smaller initial change (2.4°) than the other two wires (3.4° and 3.7°).

Rate of recovery (Table 4)

Within group comparisons: For all wire types, there was a significant difference ($P = 0.0001$) in the amount of recovery of the wires at the three temperature ranges (20.0 to 25.0°C, 25.1 to 30.0°C, and 30.1 to 36.0°C). The results also indicated that the most change, i.e., shape recovery, occurred in the range of temperature between 30.1 and 35.0°C.

Between wire comparisons: There were no significant differences present in the recovery rates at each of the three temperature ranges between the three wire types.

Recovery curve comparisons (Table 5)

A multivariate ANOVA was conducted to examine the interaction between temperature change and recovery rate of the wire. The sum of the squares of variation was partitioned into those attributable to temperature, shape recovery and the interaction between temperature and

Table 4
Changes in the recovery angle of the wires (in degrees) at various temperature ranges

Temperature Change	Wire #1 $\bar{x}$	Wire #1 S.D.	Wire #1 Range	Wire #2 $\bar{x}$	Wire #2 S.D.	Wire #2 Range	Wire #3 $\bar{x}$	Wire #3 S.D.	Wire #3 Range
20.0 - 25.0 C	5.6	4.1	1.3 - 14.0	1.3	2.3	2.4 - 9.6	5.5	3.2	2.5 - 9.8
25.1 - 30.0 C	16.7	10.6	1.2 - 41.5	17.1	8.3	3.8 - 33.0	13.1	8.2	2.2 - 30.7
30.1 - 35.0 C	29.6	7.6	14.7 - 44.0	33.3	4.6	27.2 - 40.3	29.4	5.6	15.5 - 38.3
	F-Value		P-Value	F-Value		P-Value	F-Value		P-Value
	33.39		0.0001	45.58		0.0001	44.28		0.0001

recovery. The results indicated the presence of significant differences in the interactions (P = 0.001).

When the source of variation was evaluated, significant differences were present for two variables, temperature change (P < 0.001) and the shape recovery for each wire type (P = 0.045). On the other hand, there was no difference in the interaction between the temperature change and the shape recovery.

These results indicate that overall, the three wire types behaved similarly with the change in temperature, but the magnitude of the overall recovery was significantly different. When the least square means were evaluated, they indicated that the greatest rate of recovery occurred with wire #2, followed by wire #1, then wire #3.

Discussion

Shape memory effects can be regarded as a combination of two effects: thermoelasticity and pseudoelasticity.[10] Kusy[16] emphasized the need to use appropriate terms to describe the shape memory alloys, such as martensitic stabilized alloys, martensitic active alloys, and austenitic active alloys. The stabilized nitinol alloys have a predetermined wire deformation of 8% to 10%. With active alloys, the shape memory can occur as a consequence of mechanical or thermal treatment.

Buehler and Cross[2] suggested that the shape-memory is related to the capability of the alloy to alter its atomic bonding when subjected to a temperature change. At higher temperature ranges the crystal structure of the alloy is in an austenitic phase but at a lower temperature it is martensitic. The change in temperature produces what is referred to as martensitic transformation.[17]

Table 5
A Multivariate ANOVA summary for recovery comparisons of three types of heat-activated wires at three temperature changes

Source	Sum of Squares	Degrees of Freedom	F-Value	P-Value
Model	15221	8	29.75	0.0001*
Error	13943	218		
Corrected Total	29164	226		
*Sources of Variation:				
Shape recovery by wire type:	402	2	3.14	0.045
Temperature Change	14625	2	114.34	0.0001
Wire Temperature	194	4	0.76	0.5545

In an earlier study, Hurst et al.[18] tested shape recovery of thermoelastic wires after stretching them to 12% of their original length. They observed that, in general, the mean percent recovery ranged from 89% to 94%.

The results of this investigation indicate that within the testing parameters of the present experiment, shape recovery was almost 100%. Furthermore, the transition temperature range (TTR) for three commercially available thermodynamic wires are of similar magnitudes (6.7°C, 6.2°C and 6.7°C) and are not statistically significant (Table 2). The greatest difference is in their standard deviations (1.3°C, 2.2°C and 3.7°C), a property that may be dependent on the manufacturing, i.e., alloying of the wire and/or its heat treatment.

It is also of interest to note that the recovery rate seems to gradually increase as the temperature reaches the upper limit of the TTR. This behavior was consistent among the three wire types.

The results further indicate that the range of TTRs for the three wires is below the normal oral temperature. It has been suggested that if the TTR is too close to the oral temperature, shape recovery might occur while the clinician is still tying the archwire. On the other hand, if the TTR is slightly above the normal oral temperature, shape recovery might be achieved by raising the oral temperature with hot rinses.[18]

It should be noted that in the present study the relatively straight portion of the archwire was used, a future study should determine whether the curved segment of the wire would have the same recovery rate. In addition, one wire was slightly larger (.018 x .025) than the other two (.017 x .025). It was felt that this difference would not significantly affect the interpretation of the results.

Conclusions

The findings indicate that, in general, the three wire types tested perform similarly. The only difference that might have clinical implications is related to the uniformity of the performance within each wire type as indicated by the measure of variability, i.e., the standard deviation.

Author Address

Samir E. Bishara
Professor, Department of Orthodontics
220 Dental Science Bldg. S.
Iowa City, Iowa 52242-1001

S.E. Bishara, professor, Department of Orthodontics, College of Dentistry, University of Iowa, Iowa City.

J.M. Winterbottom, engineer, Department of Biomedical Engineering, University of Iowa, Iowa City, Iowa.

A-H.A. Sulieman, assistant professor, Faculty of Dentistry, Mosul University, Mosul, Iraq.

K. Rim Professor, Department of Biomedical Engineering, University of Iowa, Iowa City, Iowa.

J.R. Jakobsen Assistant Professor, Department of Preventive and Community Dentistry, University of Iowa, Iowa City, Iowa.

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