Original Article

Elastic Flexural Properties of Multistranded Stainless Steel Versus Conventional Nickel Titanium Archwires*

Brian K. Rucker, PhD[a]; Robert P. Kusy, PhD[a–d]

Abstract: Based on a recent investigation that modeled the elastic properties (ie, strength, stiffness and range) of multistranded wires made from linearly elastic materials, three-stranded (triple) and six-stranded coaxial (coax) stainless steel (SS) wires were compared to single-stranded (single) SS and conventional nickel titanium (NiTi) leveling wires. To measure Young's modulus of elasticity (E), flexural tests were performed with an Instron mechanical testing machine in a three-point bending arrangement having a span length of 8.9 mm or 12.5 mm. A strong correlation between wire stiffness and the area moment of inertia demonstrated that strand interaction was negligible at low activations and that E = 199 GPa was constant even for the heavily drawn coax strands. Using the Instron with an extensometer, the 0.1% yield strengths (σ_{YS}) of the single SS wires and the straight inner strands within the coax wires were tested. The ratio of the σ_{YS} to the ultimate tensile strength averaged 0.81 for the single wires, 0.88 for the coax wires, and was subsequently assigned 0.85 for the triple wires. The average σ_{YS} values were 1.88, 1.83, and 1.78 GPa for the single, triple, and coax SS wires, respectively. For each NiTi wire, both the σ_{YS} and the elastic limit (σ_{EL}) via cyclic loading were measured. The conventional NiTi wires displayed nonlinear elasticity, as the average σ_{EL} values (1.10 GPa) were 50% higher than the average σ_{YS} values (0.73 GPa). Compared to the elastic properties of the conventional NiTi wires, the triple and coax SS wires generally matched the stiffness, but had only one-third to one-half of the strength and range. Since the properties of strength and range are both proportional to σ_{YS}, fabrication using alloys with enhanced σ_{YS} values would allow multistranded SS archwires to compete better against conventional NiTi products. (*Angle Orthod* 2002;72:302–309.)

Key Words: Archwires; Elastic properties; Multistranded; Stainless steel; Nickel titanium

INTRODUCTION

During the early leveling stages of orthodontic treatment, more physiologically acceptable tooth movement can be achieved if light, continuous forces are used rather than heavier, intermittent forces.[1] Low-stiffness wires are used to deliver these light forces, typically single-stranded nickel titanium (NiTi) wires or multistranded stainless steel (SS) wires. Linearly elastic materials that include SS and conventional NiTi, which is stabilized martensite, deliver forces that are proportional to the amount of activation.[2] These forces decrease as the teeth move and the wires deactivate. Alternatively, pseudoelastic (so-called ''superelastic'') NiTi archwires are now available[3] that deliver a nearly constant force over a span of activations—ideally those that occur between office visits. However, some superelastic NiTi products have tested comparable to conventional NiTi wires,[4] and only in certain instances have superelastic NiTi wires significantly outperformed multistranded SS wires in clinical trials.[3] As the properties of NiTi alloys are dependent on small changes in composition, Bourauel et al[5] found that superelastic NiTi appliances from the same package displayed extreme changes in force delivery. Consequently, some practitioners do not employ superelastic wires during orthodontic treatment; instead, they use the more traditional and proven leveling tools of conventional NiTi and multistranded SS wires.

A recent investigation that modeled the elastic properties (ie, strength, stiffness, and range) of linearly elastic archwires found that: (1) the three-strand twisted and coaxial

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*The authors receive no benefit of any kind either directly or indirectly from this work.

Accepted: February 2002. Submitted: October 2001.

wire configurations indeed attain the best elastic properties among basic multistranded geometries, and (2) multistranded SS archwires often matched the elastic properties of conventional NiTi leveling wires.[6] These findings were based on several assumptions, two of which were that there was no strand interaction (eg, interstrand friction) during flexure and that the stress at the proportional limit, which represents the limit of the elastic region, followed the theoretical values for SS and conventional NiTi alloys as defined in the metallurgical literature.[7] These important assumptions must be properly addressed to ensure the validity of the model and to accurately compare the elastic properties of currently available leveling wires.

In the present investigation flexural tests were performed to compare the measured and calculated stiffnesses of the multistranded wires. A strong correlation indicated that strand interaction was negligible and that Young's modulus of elasticity (E) for SS was correct and indeed constant for even the heavily drawn strands of coaxial wires. This data was combined with known E data for conventional NiTi wires.[8] The 0.1% yield strengths (σ_{YS}), which approximate the proportional limits, were measured for the SS wires and wire strands. Since σ_{YS} can be considerably affected by drawing ratios and thermal history,[9] the σ_{YS} values for the individual wire strands may be considerably different from those of the larger single-stranded wires. Although the reported values and techniques for measuring the σ_{YS} for conventional NiTi wires vary substantially,[10–12] proper evaluations for NiTi alloys require cyclic loading.[13,14] After verifying the assumptions of the model with the results of these tests, the E, σ_{YS}, and geometric parameters for each archwire were used to compare the measured properties of commercial leveling wires to their theoretical values. Specific clinical questions were then addressed by determining whether the multistranded SS wires had geometric and physical properties that maximized their effectiveness as leveling appliances, and whether improvements were required in order for the multistranded SS wires to compete with conventional NiTi wires.

MATERIALS AND METHODS

Three-stranded (triple) and six-stranded coaxial (coax) SS archwires, each from four manufacturers, were compared to single-stranded (single) SS and conventional NiTi leveling wires.

Each outer strand diameter (d_o) and axial displacement per twist of a wire strand (ℓ^*) was measured ($\pm$ 0.01 mil) at five locations using the optics of a Kentron microhardness tester (Kent Cliff Labs, Peekskill, New York) (Figure 1). Each inner strand diameter (d_i) and overall wire diameter (D) was measured ($\pm$ 0.05 mil) at five locations using a digital micrometer (μ–Mate; Sony Magnescale America Inc, Orange, Calif). The helix angles (α) of the outer twisted strands were calculated by equation 1[12]:

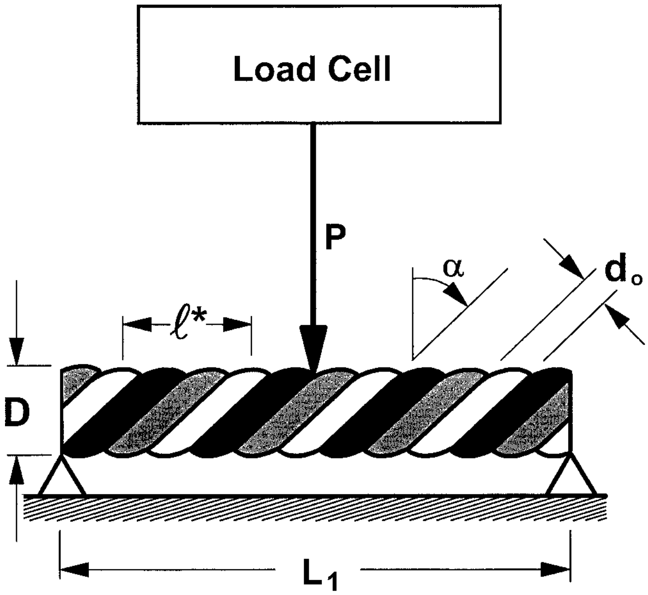

FIGURE 1. Three point bending schematic shown for a 3 stranded twisted (triple) wire. The geometric parameters needed to calculate the helix angle (α) include the outer strand diameter (d_o), overall wire diameter (D), and axial distance per twist of a wire strand (ℓ^*) [cf eq (1)]. The force (P) per unit of wire deflection (not shown) and the distance between supports (L_1) are used to determine the wire stiffness via equation 2.

$$\alpha = \tan^{-1}\{\ell/[\pi(D-d_o)]\}.$$

Using an Instron mechanical testing machine (Instron Corp, Canton, Mass) in a three-point bending arrangement, the triple wires were tested with a distance between outer supports (L_1) of 12.5 mm and the coax wires were tested with L_1 = 8.9 and 12.5 mm (cf, Figure 1). The force-deflection curves were maintained at a slope of 45 degrees to 75 degrees using a 500 kg load cell with a 200 g full-scale sensitivity. Each E was calculated by equation 2[12]:

$$E = L_1^3 P/48\delta I_{total} n$$

in which P, δ, I_{total}, and n are the force applied to the beam, the deflection of the beam under load, the total area moment of inertia, and the number of wires simultaneously tested, respectively. Note that equation 2 assumes no strand interaction and applies only to linear elastic materials. For the triple wires,[12] $I_{total} = 3d_o^4\kappa\pi/64$ in which the helical spring shape factor is $\kappa = 2\sin\alpha/(2 + \gamma\cos^2\alpha)$ and γ is Poisson's ratio, which is assigned the value of 0.28 for SS.[15] For the coax wires,[6] $I_{total} = (d_i^4 + 5d_o^4\kappa)\pi/64$. The n and maximum P in equation (2) were governed by the following criteria: the total wire deflection was $\leq 0.05L_1$; the wire deflection due to gravity was $\leq 0.0005\delta$; and, the machine deflection was $\leq 0.005\delta$.[8]

Tensile tests were conducted with the Instron machine using a 500 kg load cell, capstan grips with a nip-to-nip distance of 60 mm, and a 2 mm/min crosshead speed. Three samples were tested for each wire type and the results av-

TABLE 1. Helix Angles (α) of Stainless Steel Archwires*

Overall Wire Diameter (mil)†	Helix Angles (α) (degrees)							
	Three-Strand Twisted (Triple)				Coaxial (Coax)			
	AmO	GAC	Orm	Uni	AmO	GAC	Orm	RMO
15.5	74	71	69	82	57	53	53	55
17.5	71	67	75	80	52	57	49	51
19.5	68	64	67	81	54	58	57	57
21.5	65	61	71	80	52	55	55	53

* AmO indicates American Orthodontics, Sheboygan, Wis; GAC, GAC International, Islandia, NY; Orm, SDS Ormco, Glendora, Calif; Uni, 3M/Unitek Corporation, Monrovia, Calif; RMO, Rocky Mountain Orthodontics, Denver, Col.
† 1 mil = 0.001 in = 0.0254 mm.

eraged. To measure the ultimate tensile strength (σ_{UTS}), each sample was loaded to failure and the maximum stress was noted. To measure the 0.1% yield stress (σ_{YS}), each sample was preloaded to 1kg, mounted with a 12.5 mm extensometer that was capable of a 10% maximum strain and loaded to failure. The extensometer was attached to only the single wires and the straight inner strands of the coax wires, since straightening the twisted stands of the triple wires could alter their tensile properties. A best-fit line was drawn over the elastic loading trace and a parallel line was drawn to establish the 0.1% yield point. To measure the elastic limit (σ_{EL}), which is the greatest stress a material can withstand without showing any permanent set when the load is removed,[14] the NiTi wires were preloaded, mounted with the extensometer and cyclically loaded to a specific stress until evidence of cold-working (ie, plastic deformation) was observed. A new as-received wire was used for each iteration.

After a linear regression was fitted to the experimental data using statistical software, the corresponding correlation coefficient and the number of data points determined a probability.

RESULTS

The α values averaged 72° and 54° for the triple and coax wires, respectively, and varied from 49° to 82° (Table 1). Note that α = 90 degrees for single wires.

The d_i, d_o, σ_{YS}, and σ_{UTS} values were reported as only mean values because their standard deviations were < 5% of each mean (Table 2). For the coax wires, the d_i values were up to 40% larger but only 3% smaller than the corresponding d_o values.

When flexural tests were performed on 38 coax and triple wires (Figure 2), the slope of the linear regression line (E = 199 GPa) had a high correlation coefficient (r = .99) and a highly significant probability ($P < .001$). This data appeared to be independent of both wire configuration and L_1.

For the SS wires, σ_{YS} varied from 1.41 to 2.34 GPa, and the σ_{UTS} values varied from 1.51 to 2.68 GPa (cf, Table 2).

TABLE 2. The Diameters of the Inner (d_i) and Outer (d_o) Strands, 0.1% Yield Stresses (σ_{YS}), and Ultimate Tensile Strengths (σ_{UTS}) of Single-Stranded, Triple, and Coax Stainless Steel Archwires*

Wire Configuration	Overall Wire Diameter (mil)	d_i (mil)	d_o (mil)	σ_{YS} (GPa)	σ_{UTS} (GPa)	σ_{YS}/σ_{UTS}
Single	12*	12.24		1.70	2.20	0.77
	14*	13.64		2.34	2.49	0.94
	16*	15.72		1.94	2.43	0.80
	12†	12.20		1.89	2.25	0.84
	14†	13.90		1.62	2.20	0.74
	16†	15.58		1.80	2.29	0.79
Triple‡	15.0*		6.93		2.40	
	17.5*		7.85		2.17	
	19.5*		8.76		2.00	
	21.5*		9.82		1.57	
	15.0§		6.93		2.21	
	17.5§		7.80		2.26	
	19.5§		8.81		2.19	
	21.5§		9.73		2.10	
	15.0†		6.69		2.15	
	17.5†		8.02		1.72	
	19.5†		8.90		2.17	
	21.5§		9.94		1.51	
	15.0‖		6.75		2.68	
	17.5‖		7.83		2.51	
	19.5‖		9.07		2.48	
	21.5‖		9.94		2.42	
Coax¶	15.5*	5.44	4.88	1.91	2.29	0.83
	17.5*	6.98	4.98	1.99	2.15	0.92
	19.5*	6.94	6.04	2.05	2.30	0.89
	21.5*	7.90	7.30	2.20	2.25	0.98
	16.0§	5.30	5.48	1.53	1.81	0.85
	17.5§	5.90	5.90	2.30	2.34	0.98
	19.5§	6.78	6.92	2.27	2.65	0.86
	21.5§	7.37	6.95	1.58	1.77	0.89
	15.5†	5.46	4.89	1.41	1.68	0.84
	17.5†	6.33	5.27	1.82	1.99	0.91
	19.5†	6.36	6.50	1.59	1.97	0.81
	21.5†	7.40	6.90	1.54	1.74	0.89
	15.5#	5.46	4.89	1.41	1.68	0.84
	17.5#	6.33	5.27	1.82	1.99	0.91
	19.5#	6.36	6.50	1.59	1.97	0.81
	21.5#	7.40	6.90	1.54	1.74	0.89

* American Orthodontics, Sheboygan, Wis.
† SDS Ormco, Glendora, Calif.
‡ Extensometer not mounted on twisted strands.
§ GAC, Islandia, NY.
‖ 3M/Unitek, Monrovia, Calif.
¶ Only the straight inner strands were used so that the extensometer could be mounted.
# RMO Corporation, Denver, Col.

Neither the σ_{YS} nor σ_{UTS} values strongly correlated with strand diameter (ie, d_i for the single or coax wires and d_o for the triple wires (Figure 3, top frames). The ratio of σ_{YS} to σ_{UTS} averaged 0.81 for the single wires and 0.88 for the coax wires.

For the NiTi wires, the σ_{EL} values that averaged 1.10 GPa were as much as 80% higher than the corresponding σ_{YS} determinations (Table 3). The σ_{EL} values did not strongly correlate with strand diameter, and the σ_{UTS} values were

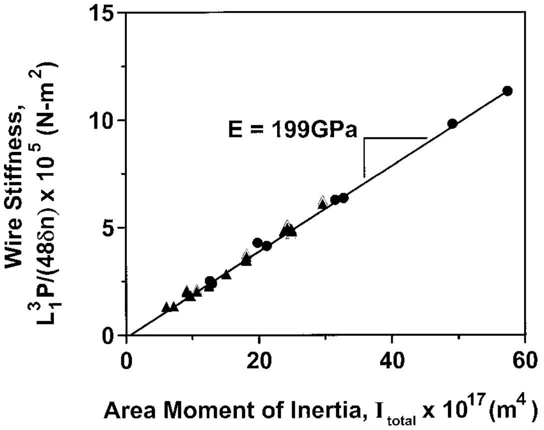

FIGURE 2. Results of 38 bending tests on multistranded SS wires. Tests included triple wires with $L_1 = 12.5$ mm [●], coax wires with $L_1 = 12.5$ mm [▲], and coax wires with $L_1 = 8.9$ mm [△]. To construct a linear equation in the form y = mx, the three-point bending formula in equation 2 is rearranged to $L_1^3P/(48\sigma n) = EI_{total}$ in which I_{total} is a function only of geometry. The slope of the linear regression of the data is Young's modulus (E). As expected, the E for SS appears to be independent of strand diameter and L_1.

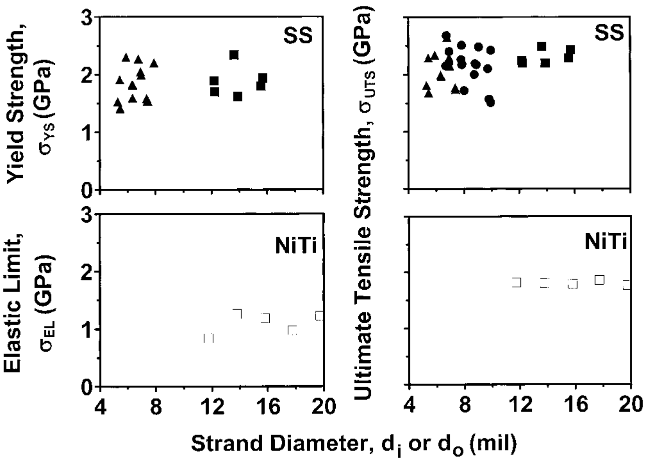

FIGURE 3. Tensile properties of archwires as a function of strand diameter. Top: the 0.1% yield strengths (σ_{YS}) and the ultimate tensile strengths (σ_{UTS}) of SS wires for single-stranded (single) [■], triple [●], and coax [▲] wire configurations. Bottom: the elastic limit (σ_{EL}) and σ_{UTS} for single nickel titanium (NiTi) [□] wires. Note that 1 mil = 0.001 in = 0.0254 mm.

nearly constant (cf, Figure 3, bottom frames). To measure the σ_{EL} of the 16 mil NiTi wires (Figure 4), plastic deformation was not evident when a wire was cyclically loaded four times to 1.19 GPa. When a new wire was tested at 1.23 GPa or higher, deformation was conspicuous on the first cycle, whereas the next three cycles showed the smaller and relatively constant amounts of hysteresis due to mechanical testing. For conventional NiTi wires in tension, both the stress (related to the strength property) and strain (related to the range property) are substantially higher for σ_{EL} than for σ_{YS} (Figure 5).

TABLE 3. The d_i, σ_{YS}, σ_{EL}*, and σ_{UTS} of Single Conventional Nickel Titanium Archwires†

Overall Wire Diameter (mil)	d_i (mil)	σ_{YS} (GPa)	σ_{EL} (GPa)	σ_{UTS} (GPa)	σ_{EL}/σ_{UTS}
12‡	11.75	0.51	0.84	1.82	0.46
14‡	13.80	0.97	1.27	1.81	0.70
16‡	15.82	0.66	1.19	1.79	0.67
18‡	17.74	0.66	0.98	1.86	0.53
20‡	19.76	0.85	1.23	1.77	0.70

* Highest stress at which plastic behavior was not evident under cyclic loading (see Figure 4).

† d_i indicates inner strand diameter; σ_{YS}, 0.1% yield strength; σ_{EL}, elastic limit; σ_{UTS}, ultimate tensile strength; and GPa, gigapascal.

‡ 3M/Unitek, Monrovia, Calif.

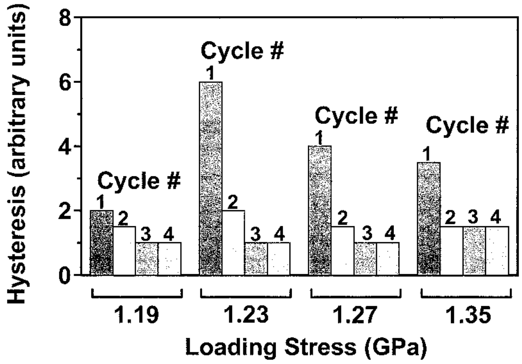

FIGURE 4. Cyclic loading tests to determine σ_{EL}. When a linearly elastic wire is loaded and unloaded in the elastic region, the force-deflection trace should return to the starting point, although mechanical tolerances of the testing apparatus account for 1 or 2 units of hysteresis. When loading exceeds σ_{EL}, cold-working (ie, plastic deformation) is shown by an increased amount of hysteresis on the first cycle. For the 16 mil NiTi wire, cold-working was evident for loading stresses of 1.23 GPa or higher. The σ_{EL} values are substantially higher than the traditionally measured σ_{YS} values (cf, Table 3).

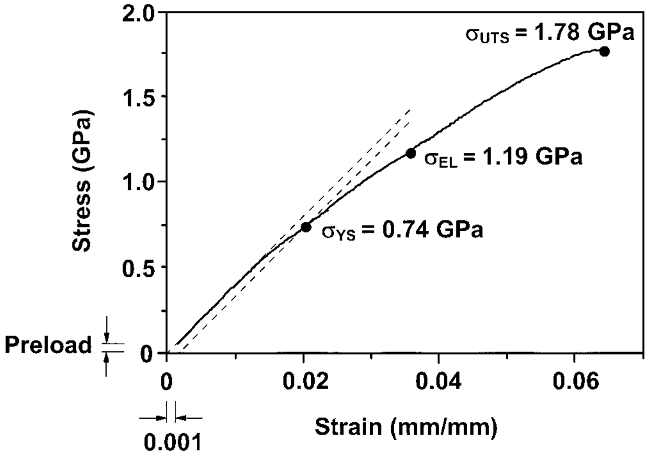

FIGURE 5. Tensile data for a 16 mil conventional NiTi wire. The σ_{EL} values for conventional NiTi wires can be substantially larger than σ_{YS} determinations, which assume linear elasticity. Consequently for the conventional NiTi wires, the ranges were somewhat underestimated and the nonlinearities of the stiffnesses at loading stresses above σ_{YS} were ignored.

TABLE 4. Average Elastic Property Ratios (EPRs) of Commercial SS and Conventional NiTi Archwires Versus a NiTi 16 mil Wire*

Archwire			EPRs		
Material	Configuration	Overall Diameter (mil)	$EPR_{Strength}$	$EPR_{Stiffness}$	EPR_{Range}
SS	Coax	15.5	0.10	0.27	0.37
NiTi	Single	12	0.29	0.30	0.97
SS	Coax	17.5	0.15	0.42	0.36
SS	Triple	15.5	0.20	0.47	0.43
NiTi	Single	14	0.71	0.58	1.2
SS	Coax	19.5	0.25	0.67	0.37
SS	Triple	17.5	0.26	0.80	0.33
SS	Coax	21.5	0.31	0.98	0.32
NiTi	Single	16	1.0	1.0	1.0
SS	Triple	19.5	0.39	1.3	0.30
NiTi	Single	18	1.2	1.6	0.75
SS	Single	12	0.70	1.7	0.41
SS	Triple	21.5	0.46	1.9	0.24
NiTi	Single	20	2.0	2.4	0.83
SS	Single	14	1.1	2.7	0.41
SS	Single	16	1.5	4.4	0.34

* SS indicates stainless steel; and NiTi, nickel titanium.

DISCUSSION

Elastic property ratios

For the SS wires, the elastic property ratios (EPRs) were initially calculated (Table 4) using the corresponding α (cf, Table 1) and σ_{YS} (cf, Table 2) values and E was assigned the value of 199 GPa (cf, Figure 2). The σ_{YS} values were used to estimate the σ_{PL} values (see Table 1[6]). Previous work showed that the ratio of σ_{YS}/σ_{UTS} for SS wires generally increased as the strand diameter decreased (eg, 70% to 80% for single wires).[16] Since here the ratio of σ_{YS}/σ_{UTS} averaged 0.81 and 0.88 for single and coax wires, respectively (cf, Table 2), the σ_{YS} of each triple wire was assigned 85% of the average σ_{UTS} of the wire's strands. The EPRs for the SS wires were averaged among manufacturers for each wire size and type. To compute the EPRs of the conventional NiTi wires, the σ_{EL} values were used to estimate the σ_{PL} values and E was assigned the value of 44.4 GPa.[8] Because stiffness is often the first consideration in wire selection,[17,18] wires in Table 4 are listed by increasing stiffness. The multistranded wires had $EPR_{Stiffness}$ values that varied from 0.27 (coax 15.5 mil wire) to 1.9 (triple 21.5 mil wire); that is, the multistranded wires had from approximately one-third to twice the stiffness of a 16 mil NiTi wire. All multistranded wires that had stiffnesses lower than a 16 mil NiTi wire ($EPR_{Stiffness} \leq 1.0$) had low strengths ($EPR_{Strength} \leq 0.31$). The ranges of the multistranded wires ($0.24 \leq EPR_{Range} \leq 0.43$) were basically no higher than that of the single 12 or 14 mil SS wires. Separate nomograms are plotted for each nominal diameter to compare visually the performances of commercial triple and coax SS wires to alternative leveling archwires (Figures 6–9). For the same D, the coax wire had noticeably lower stiffness and strength than the triple wire.

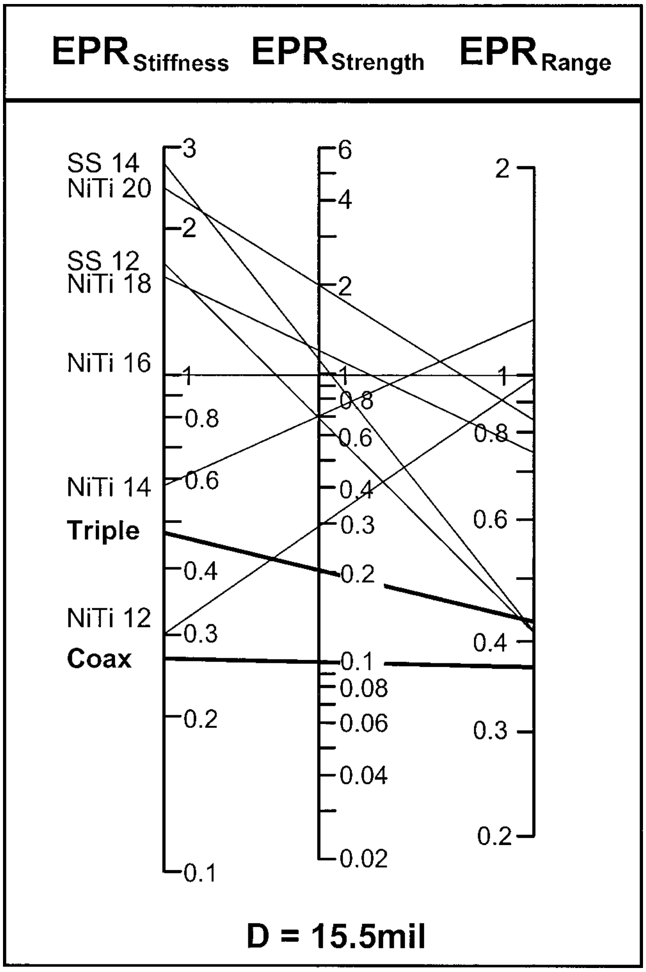

FIGURE 6. Nomogram comparing the elastic property ratios (EPRs) of commercial triple and coax SS wires (for a nominal overall wire diameter (D), D = 15.5 mil) to alternative leveling archwires. For Figures 6–9, the EPRs were calculated using a 16 mil NiTi wire as the baseline and averaged between manufacturers.

Previous findings

Regarding strength, the σ_{YS} of wires can differ noticeably between manufacturers and even between wire sizes within a product line due to strain hardening during the wire-drawing process.[9] Based on various modes of bending and tensile tests performed on as-received products, σ_{YS} averaged 1.95 GPa and E averaged 188 GPa for SS archwire[11,16,19–21]; whereas, σ_{YS} averaged 0.45 GPa and E averaged 37 GPa for NiTi archwires.[8,10,11] About a three-fold increase was noted between the current σ_{EL} values (Table 3) and these reported σ_{YS} values for NiTi. This discrepancy arises because previous investigators measured the yield strengths assuming that conventional NiTi follows linear elasticity.

Regarding stiffness, several archwires have been studied by various investigators.[17,18,22,23] Each column in Table 5

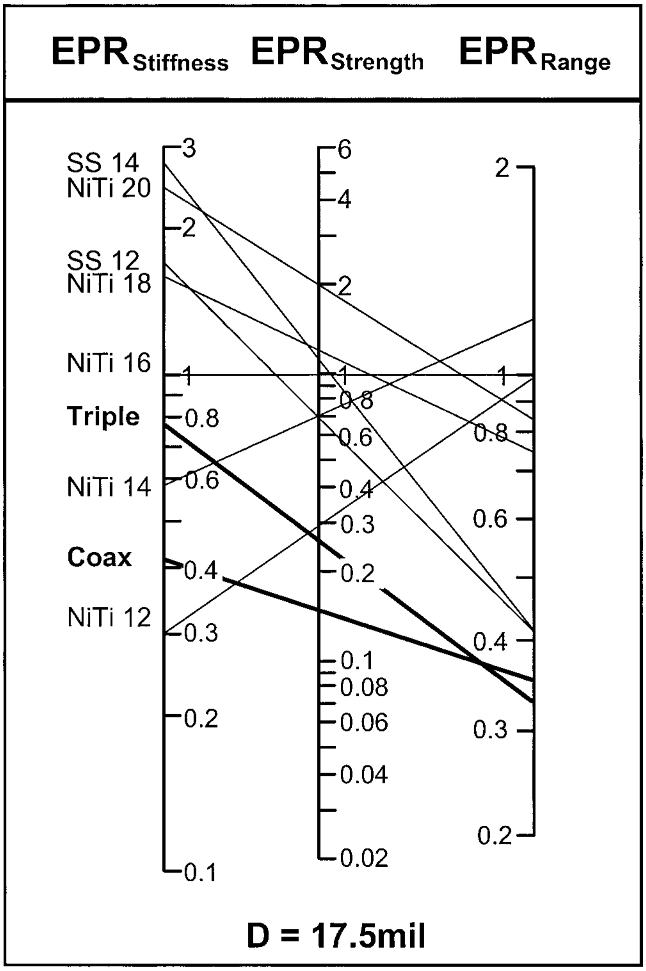

FIGURE 7. Nomogram comparing the EPRs of commercial triple and coax SS wires (nominal D = 17.5 mil) to alternative leveling archwires.

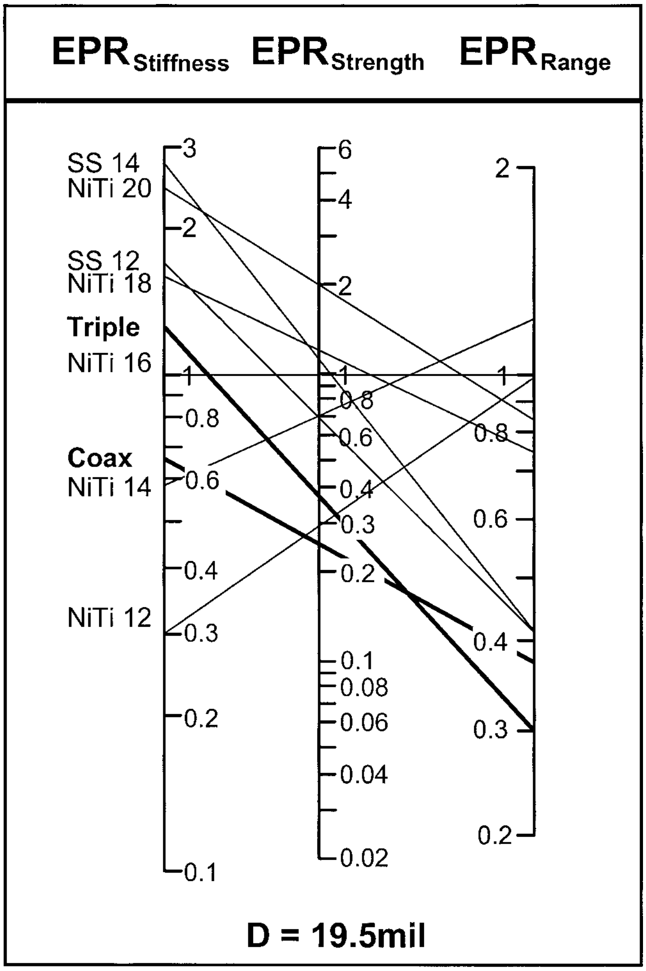

FIGURE 8. Nomogram comparing the EPRs of commercial triple and coax SS wires (nominal D = 19.5 mil) to alternative leveling archwires.

was normalized by the stiffness value of the 16 mil NiTi wire that was reported in each particular investigation. Compared to previous results, the current $EPR_{Stiffness}$ values were surprisingly similar given the variability in E measured on SS archwires (96 to 232 GPa).[10,11] Stiffness, the product of E times I, can be measured from the slope of a load-deflection curve in the elastic region assuming linear elasticity. Consequently, relative stiffnesses can be measured without knowing the absolute values of E (a material parameter) or I (a geometric factor). However, the present expressions that model the elastic properties wires depend wholly on strand symmetry and non-interaction. Because engineering mechanics still lacks a systematic approach to predict the properties of wires having braided-, soldered-, or swaged-strand configurations, orthodontics cannot calculate the elastic properties of those wires either.

Regarding range, few data are available because direct measurements are difficult and arbitrarily defined. Ingram *et al*[24] determined relative range by wrapping wires around mandrels of decreasing diameter until a minimum amount of permanent set was achieved. As helix angles were not noted, the reported range values for the triple and coax wires depended on the manufacturer. For multistranded wires, these ranges were generally greater than the single SS wires and always less than the single NiTi wires. The corresponding values in this study were mostly the same as the single SS leveling wires (cf, Figures 6–9 and Table 4).

Materials in perspective

Compared to conventional NiTi wires, current multistranded SS products generally matched the stiffnesses but had lower strengths and ranges, both of which are proportional to σ_{PL}. For multistranded SS wires, a theoretical investigation[6] assumed values for σ_{PL} from 1.03 to 3.28 GPa, although the measured σ_{YS} values here averaged 1.83 GPa for the triple wires and 1.78 GPa for the coax wires. The coax geometry was introduced to provide lower stiffness and higher range, but the physical properties of currently

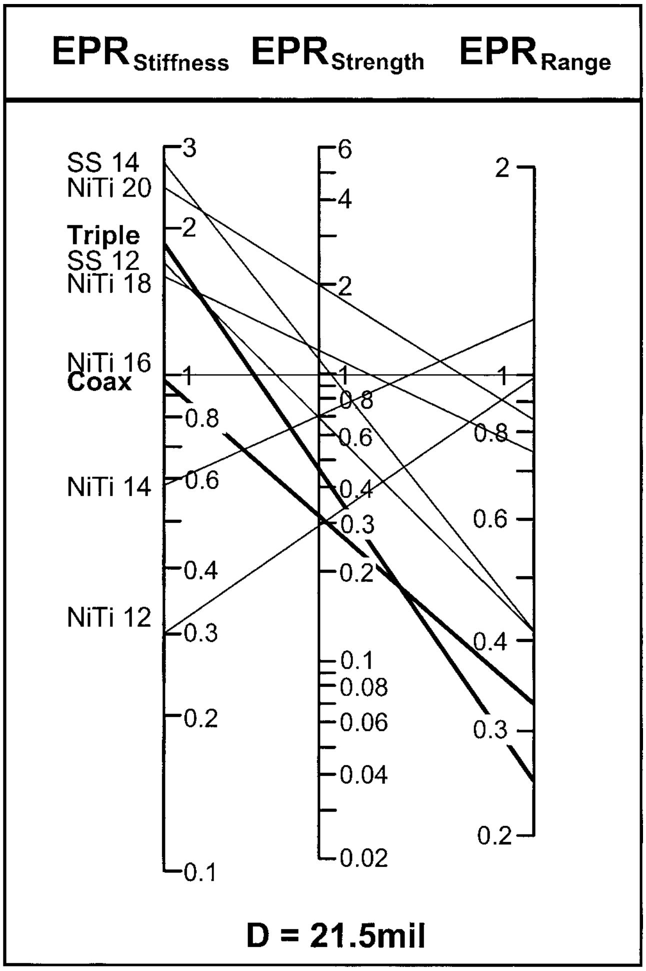

FIGURE 9. Nomogram comparing the EPRs of commercial triple and coax SS wires (nominal D = 21.5 mil) to alternative leveling archwires.

used SS alloys result in no improvement in range over single SS leveling wires (cf, Figures 6–9). For conventional NiTi wires, the same theoretical investigation[6] assumed a value of σ_{PL} = 1.24 GPa, which is within 15% of the measured σ_{EL} average of 1.10 GPa. These NiTi wires had 2–3 times the strength and range of the multistranded SS wires; ironically, the present σ_{EL} values average 2–3 times higher than previously reported values.[8,10,11]

Changes in current wire geometries, such as lowering the α values, would mildly increase the range of multistranded SS wires, but substantial improvements in strength and range must result from increasing the σ_{PL} of the materials. As was revealed by the tensile properties of the triple and coax wires (cf, Table 2), generalizing about the σ_{YS} of the heavily drawn SS strands is difficult since a number of drawing and annealing stages may occur during wire fabrication. Overall, the benefits of producing multistranded wires using high-strength SS alloys are not currently exploited because companies that produce springs and multistranded wires use lower-strength SS to gain formability[25]; higher elongation affords closer tolerances during fabrication and prevents premature fracture. To match the strength and range of the NiTi products, the σ_{YS} of the SS strands must be approximately doubled to a value of 3.5 GPa. Such strengths are not possible. Notwithstanding, the best strengthening technique for SS alloys may include precipitation hardening, since the strongest alloys are produced by combining the effects of a fine precipitate and strain hardening.[26] Such strengthening mechanisms have been used in cobalt chromium archwires in which a tradeoff occurs between resilience and formability. In that alloy, practitioners first exploit high formability during wire shaping and manipulation, then heat-treat the wire to enhance the resilience, elastic strength, and working range. Metallurgists have shown that, when plastic deformation precedes the aging treatment, a finer dispersion of particles are produced at the dislocations in the matrix.[26] By using a suitable SS alloy, perhaps multistranded wires can be precipitation-hardened in their final form after being plastically deformed during fabrication. By implementing an appropriate and cost-effective strengthening mechanism, the strength and range of NiTi products could be better matched. Then the 1989 statement by Arthur J. Wilcock might hold true for leveling wires today, namely, ‘‘that by employing ultra high

TABLE 5. Elastic Property Ratio for Stiffness ($EPR_{Stiffness}$) of Leveling Archwires in Current and Previous Investigations Versus a 16 mil NiTi Wire*

Archwire			$EPR_{Stiffness}$				
Material	Configuration	Overall Diameter (mil)	Current Work	Johnson and Lee[17]	Burstone[18]	Kusy and Stevens[22]	Oltjen et al[23]
SS	Coax	17.5	0.42	0.47	0.38	—†	0.68
NiTi	Single	14	0.58	0.95	0.59	—†	—†
SS	Triple	17.5	0.80	0.63	0.92	0.71	1.3
NiTi	Single	16	1.0	1.0	1.0	1.0	1.0
NiTi	Single	18	1.6	1.3	1.6	1.3	1.5
SS	Single	12	1.7	1.3	1.2	—†	—†

* SS indicates stainless steel; and NiTi, nickel titanium. Each investigation was normalized by its corresponding 16 mil NiTi wire.
† Data not reported.

tensile wires, stainless steel still has a major role to play in orthodontic wires.''[25]

CONCLUSIONS

Conventional nickel titanium (NiTi) archwires display nonlinear elasticity to the extent that traditional yield strength determinations, which assume linear elasticity, can grossly underestimate the elastic properties of strength and range.

Multistranded stainless steel (SS) archwires do not match the strength and range of conventional NiTi wires because they are fabricated with SS alloys that possess moderately high yield strengths.

ACKNOWLEDGMENTS

The authors thank the following product vendors for their donation of archwires: American Orthodontics, GAC International, 3M/Unitek Corporation, SDS Ormco and Rocky Mountain Orthodontics.

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