On the selection and preparation of a wire for the labial bow of an orthodontic retainer

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Following active orthodontic treatment, an orthodontic retainer is often fabricated for the patient to maintain the corrected archform during the period when relapse is likely to occur. The retention phase may last for several years, and during that time the retainer may be removed and replaced many hundreds of times.

The labial bow of a removable orthodontic retainer is, during its service life, exposed to two separate forms of undesirable mechanical action. A loading-unloading cycle is repeated with each placement and removal of the retainer. Over time the wire may fail by progressive fracture resulting from material-fatigue. Another potential mode of bow failure is distortion from its prepared shape; inelastic bending may result from the exertion of excessive masticatory forces. Such permanent deformation of the labial bow may render it less effective in holding the teeth in their corrected alignment, and may "activate" the bow toward creation of undesired forces and tooth-movements.

Previous experimental studies reported by Nikolai et al.[1] have examined the effects of material (alloy), diameter, as-received temper, canine loop height, wire surface markings/scratches, several heat-treatment temperatures and times at temperature, and procedures for removal/replacement of the retainer by the patient on the fatigue-life of prepared retainer bow wire. Some resilience tests have also been performed. This investigation was undertaken to clarify the mixed outcomes of prior experiments, to more fully explore the role of resilience testing in the process of seeking a "best" retainer-wire, and to evaluate a new wire recently marketed for removable-appliance application.

The previous article described the removable

Abstract

The Hawley retainer is often prescribed by the practitioner for part-time wear during the retentive period subsequent to a program of active, maxillary arch, orthodontic therapy. The labial bow of this retainer, while engaged, may be subjected to contact forces from sources other than the maxillary anterior teeth. The bow also experiences small deformations during placement and removal of the appliance from the oral cavity. Potential failures of the bow are: 1) inelastic bending from individual masticatory actions that change its as-prepared shape; and 2) fracture due to fatigue arising from many cycles of removing and replacing the retainer. Reported in this paper, a sequel to a previous article,[1] are the outcomes of two experiments and a nonparametric analysis that led to the development of a set of recommendations pertaining to the selection of the wire and preparation of the labial bow. Controlled variables in this study were as-received size, alloy and temper of the wire, and heat-treatment following fabrications of bow-specimens.

Key Words

Orthodontic retainer • Labial bow • Wire temper • Fatigue • Resilience • Heat treatment

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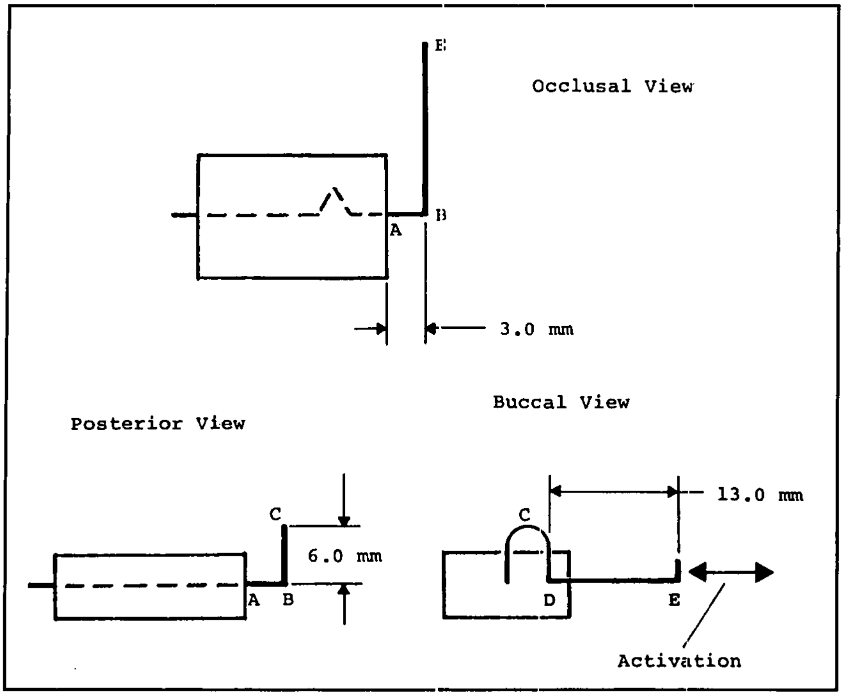

Figure 1
Specimen for fatigue-life experiment: three views of schematic of prepared half-bow embedded in and to be cantilevered from acrylic block. Location (site E) and direction (toward anterior) of cyclic activation shown.

Hawley appliance[2] and the phenomenon known as fatigue in dental as well as general metallurgic settings. An overview of work-and-energy as an analysis procedure and a basis for explanations of test results may first be worthwhile.

Failure of a component in a machine or structure is an interference with its intended function. For the labial bow, that function is to prevent displacement of tooth crowns from their corrected positions. The bow fails if 1) its as-prepared shape is altered by, for example, a single masticatory action that causes inelastic deformation or 2) it fractures after accumulating material damage from the many removals of the retainer from its position in the oral cavity and subsequent replacements. A catalyst may be associated with each potential failure. Although excessive mechanical stress or deformation may produce failure, the two failure modes cited above may be related to the energy stored in the bow and changes in levels of stored (internal) energy resulting from mechanical and/or thermal processes.

The design of machines and their structural parts is often based on a theory of failure. The total-energy theory predicts inelastic action at a specific site when the internal energy density becomes excessive and suggests a finite energy capacity which, if exceeded, results in a sudden release of energy.[3] Substantive portions of the total energy in an orthodontic appliance member are strain and thermal energies.[4] Energy may be transferred in a controlled manner as work or heat. Resilience and toughness are the capacities of a passive body to accept transferred energy in the form of mechanical work to its elastic-limit and fracture states, respectively. Ductility is the difference between toughness and resilience. Heat-transfer processes may be undertaken to increase or decrease the internal energy of a body; an anneal substantially reduces the energy stored in a body, and if occurring when not desired, is rightfully considered a failure.[5] The level of stored energy in an orthodontic appliance member as-received, for example an archwire, is known only in relative terms. Also, internal energy is not uniformly distributed throughout a body; locations of high stored-energy density are potential sites for failure.

Materials and methods

Two experiments were undertaken on the bench: 1) simulated, cantilevered half retainer-bows were subjected to sinusoidal load cycling (reference: zero force) until fractures occurred; and 2) straight segments representing anterior portions of retainer bow wires were bilaterally supported and statically deflected at midspan with continuous load-deformation plots generated to states clearly beyond elastic limits. Resilience and the number of cycles to fracture were the dependent variables measured.

Specimens for both experiments were initially segments of wire 75 mm in length, cut from the straight "sticks" received from the vendors. For the first experiment, the senior author first marked each segment with a wax pencil to denote permanent bend locations; he then placed the bends with an orthodontic loop-forming plier, beginning with the "V" and proceeding through site E as denoted in the schematic, Figure 1. Each prepared half-bow was superimposed on a template to check shape and dimensions; any half-bow that did not match the template, or was subjected to repeated reverse bending (to achieve the desired shape), was discarded, and a replacement was fabricated. Each wire segment for the second experiment remained passively straight. The as-prepared shapes of wire segments aside, controlled independent variables and their "values" were the same in both experiments: wire cross-section (0.71 and 0.91 mm [0.028 and 0.036 inches] in diameter), wire alloy and as-manufactured temper (designated for three of the four wires), and heat-treatment temperature and time-at-temperature for prepared segments as given in Table 1. (Heat treatments were undertaken in a calibrated, preheated, dental furnace; cooling was in room-air.) Subsequent to heat-treatment, if any, the medially directed portion of each bent-wire half-bow was embedded in an acrylic block (Figure 1). An alginate mold held the resin and the half-bow in place during cold-curing. The "V" bend pre-

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vented twisting of the portion of the bent-wire segment within the block during testing.

The cycled-load tests were conducted with the apparatus shown schematically in Figure 3 of the previous article;[1] the bent-wire specimen was cantilevered from the acrylic block. The static-flexure tests were undertaken using a prepared load frame and a universal testing machine. Pilot tests were run to determine instrumentation settings. Hypothesizing an endurance limit of 4500 cycles (representing removal and replacement of a retainer three times daily for 2 years), the anteriorly directed amplitude of cyclic displacement (site E, Figure 1) was 3.2 mm and the cycle frequency was 200 per minute, yielding a typical test time of 5 to 20 minutes without unwanted contributions from inertial effects. The flexure specimen was subjected to a six-point, "split-anchorage," symmetric, static-bending test as shown schematically in Figure 2. The supports represented the bow-ends embedded in the acrylic plate and the load-blade a somewhat distributed force. The span of 60 mm is approximately the curvilinear length of an average labial bow. The movable crosshead and recorder-paper speeds during the static test were chosen as 10 and 100 mm/min, respectively, giving a "magnification ratio" (of the deformation scale) of ten. The load range was zero to 5,000 grams. Passive, vertical clearance between the straight wire specimen and adjacent knife-edge (Figure 2; to permit unencumbered local specimen sliding) was 0.05 mm.

Cell sizes of 10 and six were chosen for the cycled-load and static-bending tests, respectively; the larger number of replications for the former was assumed warranted by the relatively intricate specimen preparation. The number of cells within the two experiments was equal at 18; total specimens included in the two samples were 180 and 108, respectively. The two experiments were conducted sequentially, but in both experiments the order of tests was fully randomized. The fracture of a specimen stopped the fatigue-testing apparatus, and the number of cycles to failure was read from a counter. A notable decrease in the slope of the load-deflection plot signaled the end of a static-bending test. On the plot, the elastic-limit point was approximated by the offset method (offset = 0.2 mm), and the resilience was quantified as the area under the plot to the elastic limit in gram-mm; see Figure 3. Values of the dependent variables were entered into separate files in a personal computer, and, because of the nonfactorial design, a total of six analyses of variance were performed with hard-disk-stored SYSTAT (Version 5.0) software. Arrays of cycles-to-fracture and resilience means were prepared as designated by the summary-results, and Tukey's HSD post-hoc tests isolated statistically significant, pairwise differences in generated means.

Table 1
Heat-treatment temperatures and times-at-temperature for each of four wires identified by trade-name

Wire		Temperature	Time at Temp
Elgiloy, "Yellow"*	NHT	—	—
Multiphase**	NHT	—	—
		482 deg C	12 minutes
Truchrome-Retainer*	NHT	—	—
		500 deg C	10 minutes
		850 deg C	10 minutes
Truchrome-Resilient*	NHT	—	—
		500 deg C	10 minutes
		850 deg C	10 minutes

NHT = No heat-treatment
C = Celsius
*Co-Cr-Ni-alloy and stainless-steel wires, supplied by Rocky Mountain Orthodontics, Denver, CO
**Co-Cr-Ni-alloy wire, supplied by American Orthodontics, Sheboygan, WI

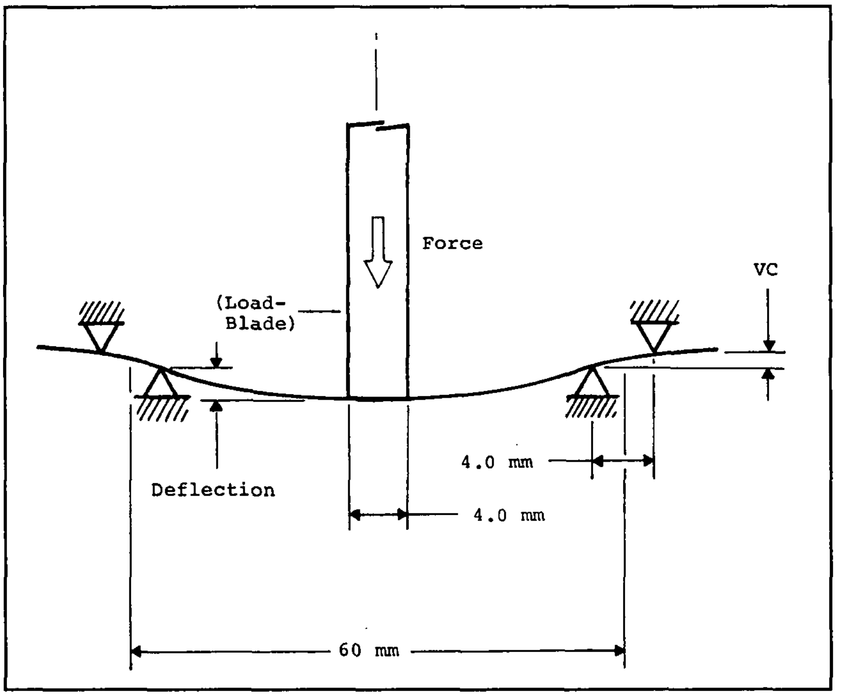

Figure 2

Figure 2
Schematic showing four knife-edge supports, load-blade, and wire-segment specimen during static bending test. Vertical clearance at supports, VC, was the wire-specimen diameter + 0.05 mm.

Results and discussion

In the first experiment, the bent-wire specimens were subjected to cycled deformation; bending occurred throughout most of the half-bow, but combined bending and twisting was observed within the 3.0-mm segment emerging from the acrylic block (Figure 1). The displacement amplitude of 3.2 mm

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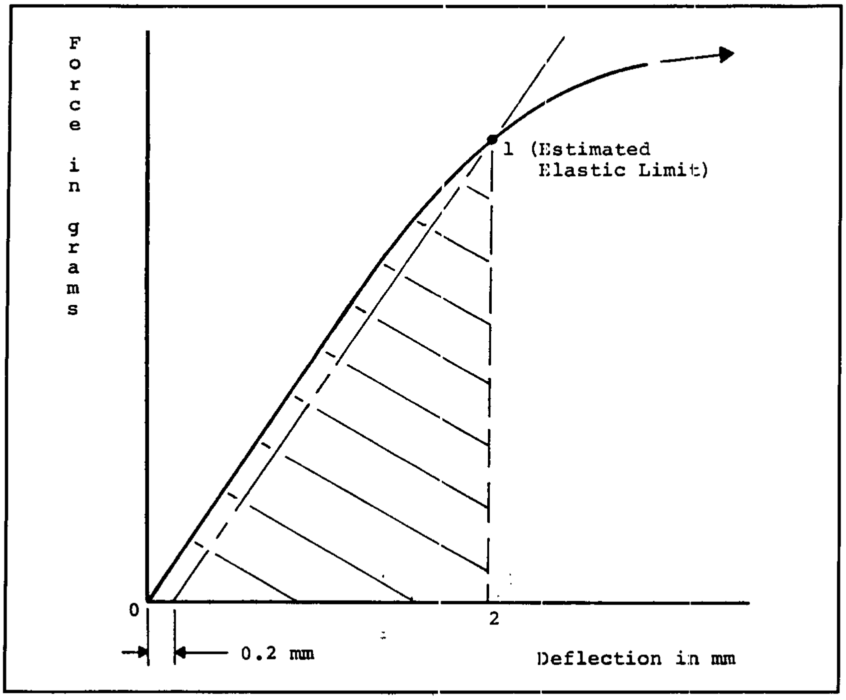

Figure 3
Representation of typical load-deformation plot prepared by chart-recorder during static bending test. Approximation of elastic-limit point by offset method shown. Cross-hatched area 0120 equals the specimen-resilience in gram-mm.

was sufficiently small that the half-bow seemed to respond elastically; however, over many cycles the net stored energy was apparently increasing. This energy was not stored uniformly throughout the bent wire. The maximum strain-energy density per cycle is relatively high at "critical cross-sections," including sites of bend-placements. With the location and direction of activation as shown in Figure 1, internal bending couples were relatively large at sites A and C, and the majority of the fractures occurred at the canine-loop apex (site C). (With other labial bow designs and different simulations of the retainer removal and replacement processes, fractures may occur at other sites.[1])

At any specific time (referenced to the beginning of cyclic loading), generally the greater the magnitude of stored energy in a bent-wire specimen, the shorter its fatigue-life. The energy transferred per cycle into the specimen was directly related to the wire diameter, and, on any specific cross-section, the maximum strain-energy density was proportional to the diameter. These relationships accounted for the outcomes from the main-effect influence of diameter on number of cycles to failure. Also to be noted in Table 2 is the rank order of wires, of a common diameter and not heat-treated, by fatigue-life; combinations of metallurgy (two Co-Cr-Ni-alloy and two Cr-Ni-steel wires) and as-received stored energies are the bases for this set of outcomes. Nonheat-treated, "yellow" Elgiloy wire segments were selected as the baseline subsamples in these experiments as a result of their previous performances.[1]

Continuing to focus on Table 2, the low-temperature heat-treatments led to somewhat smaller mean numbers of cycles to fracture from the Multiphase and Truchrome-Retainer half-bows, but had no significant effects on the fatigue-lives of the Truchrome-Resilient half-bows. Apparently the heat-treatments slightly increased the stored energies in the Multiphase and Retainer bent wires, but the Resilient wires seemingly "lost" as much energy as was delivered to them in the heat-treatment process. Although the two Truchrome wires are likely metallurgically identical, their manufacturing processes differ, probably most notably in the final steps, to produce wires of unlike ductility; accordingly, the same heat-treatment had differing effects on these two stainless steel wires. Now examining the outcomes involving high-temperature heat-treatments of the steel wires, both the Resilient- and Retainer-wire half-bows exhibited reduced fatigue-lives, apparently commensurate with increased pre-test strain energies from these heat-treatments. Comparing across wires, the mean numbers of cycles to failure of the nonheat-treated steel half-bows were significantly different; the low-temperature heat-treatment of the prepared bent-wires resulted in only a trend toward a difference, and the high-temperature heat-treatment resulted in statistically equal fatigue-lives.

During the static-bending test, energy was transferred in the form of mechanical work into a passively straight wire segment (of a Hookean material) until its strain-energy was increased to produce a clearly nonlinear and inelastic force-deflection relationship. The segment was then unloaded, and permanent deformation was verified. Figure 3 shows the typical force-deflection plot and the quantification of resilience as the area under the curve to the elastic limit.

The outcomes of the analyses of variance of resilience across the wire-segment sample are partially explained by a corollary to the total-energy theory of failure which suggests a direct relationship between the stored energy in the as-prepared specimen and its resilience.[3]

The overall pattern of resilience results may be seen in the array of the 18 cell means (Table 3). Main-effect outcomes were 1) larger resiliences obtained from the wires of the greater diameter, simply because of unlike strain-energy capacities related to volume of material and 2) the Truchrome-Resilient wires generally exhibited the greatest resilience of the four wires, related to metallurgy and manufacturing processes. Comparing across the four, 0.71-mm-diameter, non-heat-treated wires, however, the resilience of the Truchrome-Resilient wire was not significantly greater than that of the

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Table 2
Mean cycles to fracture from cells of half labial-bows
Tukey's HSD = 312 cycles

Wire	NHT 0.71	NHT 0.91	500* 0.71	500* 0.91	850 0.71	850 0.91
Elgiloy	3801	3310	—	—	—	—
Multiphase	2152	1253	1958	1027	—	—
Truchrome-Retainer	1760	1183	1528	984	893	401
Truchrome-Resilient	1304	970	1341	847	966	525

Heat-Treatment Temperature; Diameter (mm)

*Multiphase-wire specimens were heat-treated at 482 deg C.

Table 3
Mean resiliences in gram-millimeters from cells of wire-segments subjected to static bending
Tukey's HSD = 1680 gram-mm

Wire	500* 0.71	500* 0.91	NHT 0.71	NHT 0.91	850 0.71	850 0.91
Truchrome-Resilient	3550	12670	3100	6740	1170	2080
Elgiloy	—	—	2840	3700	—	—
Multiphase	3660	8660	1730	3380	—	—
Truchrome-Retainer	2200	4170	1790	3030	560	1120

Heat-TreatmentTemperature; Diameter (mm)

*Multiphase-wire specimens were heat-treated at 482 deg C.

Elgiloy wire. The low-temperature heat-treatments generally increased the energies stored in the three wires, but, notably, the resiliences of the steel wires were not increased as much as that displayed by the Multiphase-wire subsamples. The high-temperature heat-treatments of the steel wires resulted in net decreases in stored energies and commensurately smaller resilience-magnitudes compared to those of the non-heat-treated subsamples.

Examination of the comparable outcomes of the previous research[1] and the present study tends to clarify and reinforce the validity of the reduced-data obtained. The influence of wire diameter, the superior fatigue-life of the Elgiloy wire, the fatigue-life and resilience rankings between the two steel wires, and the influences of low- and high-temperature heat-treatments on the numbers of cycles to fracture and resiliences of the steel wires are not markedly different between the two articles, despite some minor differences in half-bow specimen designs and activation formats. Larger sample sizes in the present experiment helped to differentiate some outcomes that could not be shown as significantly different in the earlier study.

The fatigue-life and resilience results tend to be inversely related. The greater the level of stored energy in the as-prepared wire, the fewer the number of cycles to fracture and the greater the resilience. If the stored energy level is relatively low, the fatigue-life is substantial, but the resilience is only moderate. The ideal labial bow should exhibit a long fatigue-life and high resilience. Also of importance is the relative ease or difficulty of fabricating the bow from a straight "stick" of as-received wire; recall that the bend locations are sites of large strain-energy densities. Accordingly, toward identifying the "ideal" as-prepared bow, considering the various parameters controlled or influenced by the practitioner that have been included in the designs of these and the previous experiments and their outcomes, Table 4 was prepared. The three key variables—fatigue-life,

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Table 4
Nonparametric assessments from the outcomes of the fatigue-life and static-bending tests and including difficulty in bending half labial-bows

Subsample	Fatigue Life	Resilience	Bending Difficulty	Total
Wire Diameter = 0.71 mm				
Elgiloy-NHT	1	11	3	15
Truchrome- Resilient-NHT	8	10	4	22
Truchrome- Retainer-NHT	5	14	1	20
Multiphase-NHT	3	15	2	20
Truchrome- Resilient-LTHT*	7	7	4	18
Truchrome- Retainer-LTHT	6	12	1	19
Multiphase-LTHT	4	6	2	12
Truchrome- Resilient-HTHT*	14	16	4	34
Truchrome- Retainer-HTHT	15	18	1	34
Wire Diameter = 0.91 mm				
Elgiloy-NHT	2	5	9	16
Truchrome- Resilient-NHT	13	3	11	27
Truchrome- Retainer-NHT	10	9	5	24
Multiphase-NHT	9	8	7	24
Truchrome- Resilient-LTHT	16	1	11	28
Truchrome- Retainer-LTHT	12	4	5	21
Multiphase-LTHT	11	2	7	20
Truchrome- Resilient-HTHT	17	13	11	41
Truchrome- Retainer-HTHT	18	17	5	40

*LTHT = Low-temperature heat-treatment (482 or 500 deg C)
**HTHT = High-temperature Heat-treatment (850 deg C)

resilience, and "bending difficulty" – were weighted equally in this nonparametric evaluation. Scores were assigned to the various variable-value combinations and entered into the array; the "best" score was one. The three scores in each row were added to yield the total. The total scores were then compared. Notably, the lowest total scores were obtained for the small-diameter, low-temperature heat-treated, Multiphase wire and the non-heat-treated Elgiloy wires.

Summary and conclusions

A pair of experiments has been designed and executed to complement a previous study[1] with the objective of selecting wire alloy, as-received temper, cross-sectional size, and post-fabrication heat-treatment (if any) to maximize the service-life of the labial bow of a removable orthodontic retainer. Of primary concern in the research design were the potentials for progressive fracture due to material-fatigue and the delivery of an isolated mechanical action to cause an inelastic response. A total of 180 half-bow specimens from 18 cells were cantilevered and subjected to cycled deformation to fracture. Raw data collected were the number of cycles to failure. One hundred eight (108) labial-bow specimens, again from 18 cells, were subjected to static, split-support bending to states beyond their elastic limits. Resilience-magnitudes were determined. Null hypotheses, statistical analyses, and the resulting outcomes led to the following findings:

1. Generally, the half-bows prepared in 0.71-mm-diameter wire exhibited longer mean fatigue-lives; half-bows prepared from 0.91-mm-diameter wire showed greater resilience.
2. The low-temperature heat-treatments generally led to greater resiliences from the three wires so treated, but also to shorter fatigue-lives.
3. High-temperature heat-treatments substantially reduced both the numbers of cycles to failure and resiliences.
4. The two non-heat-treated Elgiloy-wire subsamples displayed longer mean fatigue-lives than any of the other 16 half-bow cells.
5. Among the low-temperature heat-treated subsamples, none defined by wire 0.71 mm in diameter exhibited a resilience greater than that of the Multiphase wire; also, among the 0.91-mm-diameter wires, only the Truchrome-Resilient subsample gave a mean resilience greater than that of the Multiphase wire.
6. As evaluated subjectively by the senior author, half-bow specimens were more easily prepared, and fewer potential specimens had to be discarded because of "overworking" or not matching the tem-

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plate, in the 0.71-mm wire compared to the 0.91-mm wire.

The outcomes of this study, including the non-parametric assessments displayed in Table 4, appear to warrant the following conclusions:

1. Wires of the cobalt-chromium-nickel alloys are recommended over those of orthodontic stainless steel for labial bows of orthodontic retainers.

2. The labial bow prepared in 0.71-mm-diameter Multiphase wire and subsequently subjected to the low-temperature heat-treatment recommended by the vendor may well be a reasonable alternative to the non-heat-treated bow formed in "yellow" Elgiloy wire.

3. Between the two wire sizes, the diameter of choice from the collective present results seems to be 0.71 mm. From the outcomes of the experiments reported in this and the previous article,[1] the wire-diameter of 0.81 mm (0.032 inches) may well be a compromise worthy of consideration.

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