Force application and decay characteristics of untreated and treated polyurethane elastomeric chains

Jennifer S. Stevenson, MS and Robert P. Kusy, PhD

In orthodontics, polyurethane elastomeric chains are used extensively as tooth-moving mechanisms[1] and are effective in closing diastemas, correcting rotations, shifting the midline, and achieving general space closure.[2] After placement, the elastic chains are generally changed at 3- to 6-week intervals. Once the chains are activated, they begin to permanently elongate, thus decreasing the force that they can exert on the teeth. Previous studies have indicated that untreated polyurethane elastomers undergoing stress-relaxation lose the largest amounts of force in just a matter of minutes and lose very little additional force thereafter.[3] For example, in distilled water at normal body temperature (37°C), plastic chains lose an average of about 45% of their initial force after 1 hour.[4] Thereafter, the decay increasingly stabilizes to such an extent that, over a 3-week period, only an additional 10% is lost.[5] This force decay must be taken into account in determining the load needed to produce the desired tooth movement. As much as four times the desired constant load may be required at insertion,[6] potentially causing excessive discomfort for the patient.

Two significant mechanisms account for force degradation: elastic stretch and chain slippage.[7] Elastic stretch is a reversible effect that occurs when an applied load causes individual polymer molecules to uncoil, straighten, and extend. Chain slippage occurs when an applied load causes the polymer molecules to slide past one another, resulting in permanent

Abstract

In this study the effects of prestressing, environmental acidity, oxygen content, and temperature on mechanical properties were measured for three polyurethane-based orthodontic elastomeric chains. Specimens of each chain were treated for 10 and 100 days, and their mechanical properties were compared with those of the untreated specimens via stress-relaxation tests. Conditioning treatments were determined to affect the magnitude of residual load after relaxation, with the largest effect due to prestressing. Among the other variables studied, an increase in temperature of the environment appeared to significantly influence the degradation mechanism responsible for the deterioration of the mechanical properties of polyurethane elastomers ($p<0.001$); acidity and oxygen content had no significant effects. Force decay profiles from the specimens were derived using a Maxwell-Weichert model consisting of springs and dashpots. This model allows the orthodontist to predict load magnitude supplied by the chain at activation and at any time during treatment.

Key Words

Polyurethane elastomers • Stress-relaxation • Residual load • Maxwell model

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Table 1
Characterization of untreated polyurethane elastomers

Product	Manufacturing process	Polyurethane base	Molecular weight* Number avg	Weight avg
Nihon	extrusion	polyester	137000	249000
Pellethane	injection	polyether	150000	241000
Texin	extrusion	polyester	163000	275000

*Measurements obtained by high performance liquid chromatography.

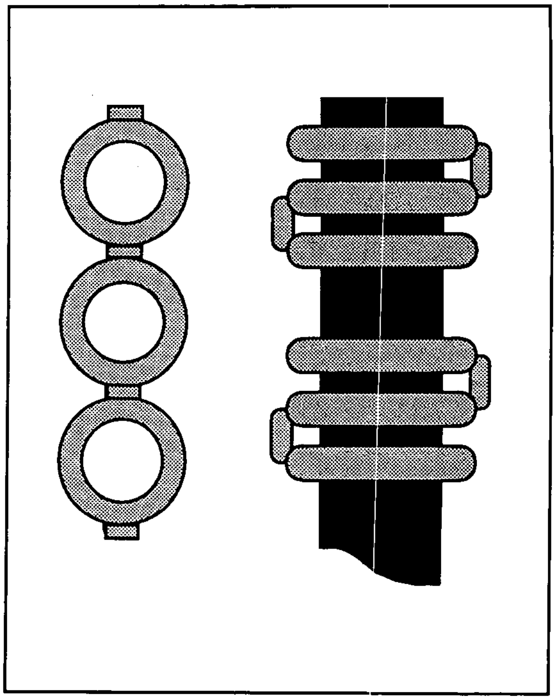

Figure 1

Figure 1
Schematic illustration of the prestressing arrangement. The unstressed chains (left-hand frame) were threaded onto stainless steel rods (right-hand frame) that elongated them by 50% (approximately 300 grams). Each rod was then placed inside an amber bottle for its conditioning treatment.

deformation. Activated orthodontic chains initially undergo the stretching process, which, if the load is sustained, is followed by the slippage mechanism. Together they identify a viscoelastic material.[8] If factors can be determined that increase the susceptibility of polyurethane elastomeric chains to force degradation, then perhaps methods to improve force decay resistance can be identified.

In this study the effects of several environmental conditions on mechanical properties were measured for three polyurethane-based elastomeric chains with different chemical formulations and manufacturing processes. Effects of acidity, oxygen content, and temperature of the chain environment were evaluated because these parameters can vary in the oral environment both transiently and among individuals. Specimens of each chain were treated for 10 and 100 days, and their mechanical properties were compared with those of the untreated specimens via stress-relaxation tests. From these force onset and force decay profiles, Maxwell-Weichert models were developed that predict the behavior of orthodontic elastomeric chains.

Materials and methods

Specimen preparation

Nihon HS90A (Nihon Unipolymer Company, Tokyo, Japan), Pellethane 2363-80A (Dow Chemical Company, Midland, Mich) and Texin 480A (Miles Corporation, Pittsburgh, Penn) polyurethane elastomers were studied (Table 1). Both the Nihon and Texin products are polyester-based polyurethanes, and the Pellethane product is a polyether-based polyurethane. The elastomeric chains were fabricated from these polyurethane pellets by Ormco Corporation (Ormco Corporation, Glendora, Calif). The Nihon and Texin chains were die-punched from an extruded strip, and the Pellethane chains were injection molded. Three-link chain segments 0.8 cm in length were chosen to simulate typical orthodontic applications. Before conditioning, all specimens were stored in the dark at -10°C to reduce any deterioration of the materials.

Conditioning treatments

To amplify the effects of the conditioning treatments and to simulate any mechanical stresses, specimens formed from three-link chains were threaded onto stainless steel rods (Figure 1). This prestressing procedure elongated the specimens by 50% and required a load of approximately 300 grams. Only the untreated control specimens (conditioning treatment 0) were not prestressed but were stored in the dark at -10°C.

Specimens of each elastomeric product were placed in one of five phosphoric buffer solutions under conditions that tested the effects of increases in environmental acidity, oxygen content, and temperature (Table 2). To achieve an environmental oxygen content of zero, specimens in conditioning treatments 1, 2, and 4 were maintained under argon, an inert gas. Specimens in conditioning treatments 3 and 5 were stored under compressed air that had an oxygen content of 21%.

The specimens underwent treatment on rods in sealed amber bottles to lessen the effects from ultraviolet light. Periodically, the containers were refilled with their designated gas and checked to ensure that no pH change, temperature variation, or solution contamination had occurred.

A set of 15 specimens (one specimen of each

Table 2
Conditioning treatments for elastomeric chains*

Conditioning treatment	Oxygen content (%)	pH	Temp (°C)
0-untreated control	-	-	-
1-conditioned control	0	7	34
2-increased acidity	0	5	34
3-increased oxygen	21	7	34
4-increased temp	0	7	44
5-combined effects	21	5	44

*Only those specimens that were subjected to conditioning treatments 1-5 were prestressed to a constant elongation of 50%.

product under each condition) was treated for 10 days. An identical set of 15 underwent the same five treatments for 100 days. At the end of the 10-day and 100-day periods, the specimens were dip-rinsed in deionized water, vacuum-dried, and stored in specimen bags in the dark at -10°C until testing.

Specimen testing

Stress-relaxation tests were executed on the 33 specimens (the 30 treated specimens and the three untreated control specimens) using an Instron Universal Testing Machine (Instron Model TTCM, Instron Corp., Canton, Mass) after 10 and 100 days of conditioning treatments. Load magnitudes were measured using a 500 kg load cell with the full scale load set to 400 grams for the prestressed and treated chains and to 1000 grams for the untreated non-prestressed chains. Preliminary investigations indicated that the compliance of the overall apparatus was negligible compared with that of the elastomeric specimens under investigation, so no corrections for machine deflection were necessary.

Testing was performed at ambient temperature (21°C). Each three-link chain was mounted in the testing machine (Figure 2) and extended at 2 cm/min from an initial length of 0.8 cm to a final length of 2.0 cm. The final length was maintained, and the force decay was recorded starting at the peak load and ending when a constant residual load was attained after approximately 5 minutes of relaxation. From the load-deflection traces, the load data were digitized for further analysis.

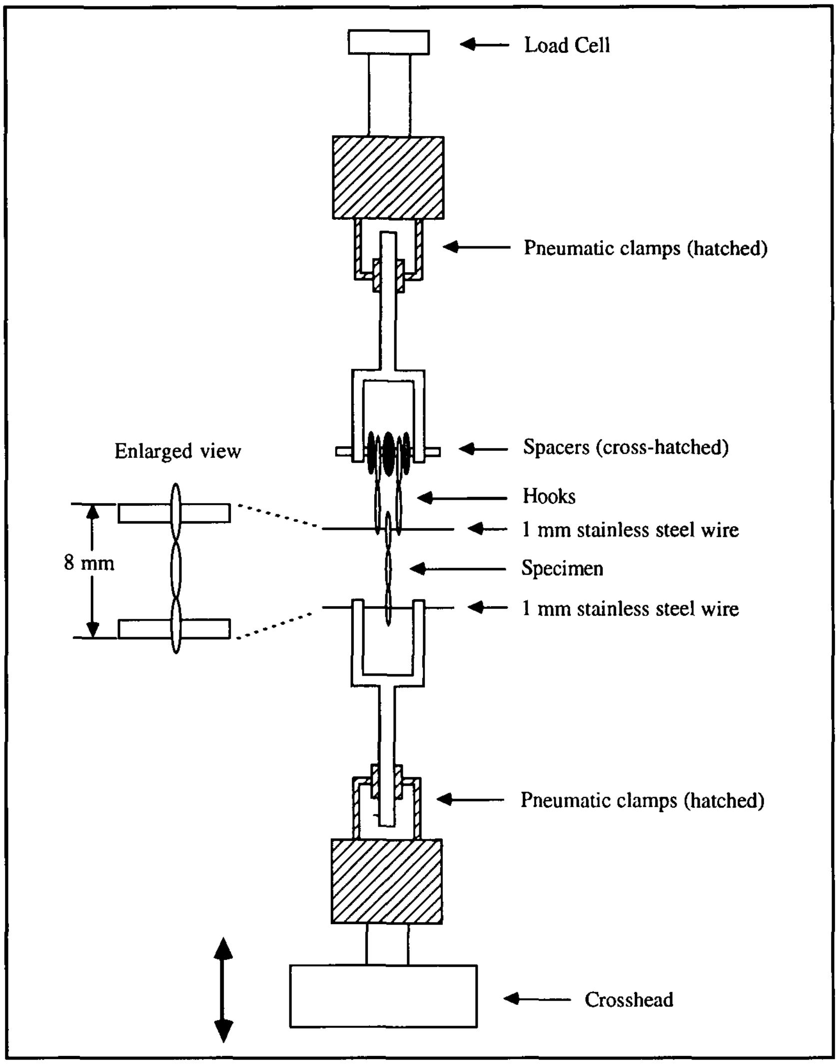

Figure 2

Figure 2
Schematic illustration of the Instron specimen mounting used in the stress-relaxation testing. The load cell measured the load on the specimen during and after the vertical movement of the crosshead (bold arrow). Compliance of the overall apparatus was negligible compared with that of the elastomeric specimens under investigation.

Data analysis

The 10-day and 100-day conditioning-treatment sets of chain specimens were analyzed for changes in their stress-relaxation profiles. Multifactorial analysis of variance was done in which the effects of conditioning treatments, treatment durations, and product were evaluated in terms of peak and residual loads. The p-values were calculated for pairwise comparisons. Coefficients for the modeling of the force decay behavior were calculated through exponential regression analysis.

Results

Load versus time plots for the untreated and treated specimens present load onset and decay regions (Figures 3 to 6). In Figure 3, the untreated, non-prestressed specimens of each product are shown. Nihon has the most favorable force-retention characteristics. Nihon

Table 3
Stress-relaxation analysis for untreated and treated specimens

Product/ treatment		Peak load (g)	Residual load (g)	Res/ peak*	Peak/ peak 0**	Res/ res 0***
Nihon						
0 day	0	500	370	0.74	1.00	1.00
10 day	1	340	268	0.79	0.68	0.72
	2	286	224	0.78	0.57	0.61
	3	320	256	0.80	0.64	0.69
	4	300	240	0.80	0.60	0.65
	5	310	246	0.79	0.62	0.66
100 day	1	278	224	0.81	0.56	0.61
	2	266	216	0.81	0.53	0.58
	3	284	226	0.80	0.57	0.61
	4	230	184	0.80	0.46	0.50
	5	216	172	0.80	0.43	0.46
Pellethane						
0 day	0	525	340	0.65	1.00	1.00
10 day	1	188	146	0.78	0.36	0.43
	2	180	138	0.77	0.34	0.41
	3	174	134	0.77	0.33	0.39
	4	164	130	0.79	0.31	0.38
	5	140	110	0.79	0.27	0.32
100 day	1	154	120	0.78	0.29	0.35
	2	156	124	0.79	0.30	0.36
	3	138	108	0.78	0.26	0.32
	4	130	106	0.82	0.25	0.31
	5	122	96	0.79	0.23	0.28
Texin						
0 day	0	485	340	0.70	1.00	1.00
10 day	1	224	170	0.76	0.46	0.50
	2	238	180	0.76	0.49	0.53
	3	240	182	0.76	0.49	0.54
	4	190	150	0.79	0.39	0.44
	5	214	162	0.76	0.44	0.48
100 day	1	204	158	0.77	0.42	0.46
	2	198	154	0.78	0.41	0.45
	3	204	158	0.77	0.42	0.46
	4	162	124	0.77	0.33	0.36
	5	160	124	0.78	0.33	0.36

* Res/peak=ratio of residual load to peak load for the same specimen.
** Peak/peak 0=ratio of peak load for specimen to peak load for untreated product.
*** Res/res 0=ratio of residual load for specimen to residual load for untreated product.

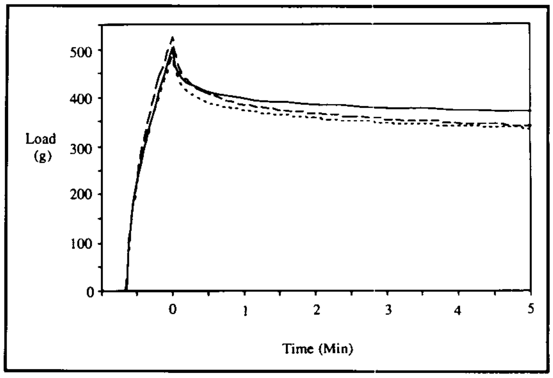

Figure 3
Load versus time curves present load onset and decay regions for the untreated, non-elongated control specimens of each product. Nihon, represented by the solid line, displays the best load retention over the time period studied. Pellethane is represented by long dashes and Texin by short dashes.

specimens for all conditioning treatments after 10 days (Figure 4A) and 100 days (Figure 4B) and the untreated specimen are shown. Due to the elongation during treatment, the chain specimens exhibited permanent deformation after both 10 and 100 days of treatment. Whereas the chains were 0.8 cm in length before treatment, all prestressed specimens were permanently extended by 50% to nominally 1.2 cm after treatment. Because the elongated, treated specimens were longer than the untreated specimens, some of the initial displacement was used to "take up the slack" in the specimens. Consequently, a time lag occurred before initial load onset for the treated specimens, and the peak load values for the treated stretched specimens were less than the peak load values for the untreated non-prestressed specimens. This peak load difference is more evident for the Pellethane specimens, which exhibited greater deformation due to treatment than did the Nihon specimens, after both 10 days (Figure 5A) and 100 days (Figure 5B). Texin specimens, after 10 days (Figure 6A) and 100 days (Figure 6B) of treatment, and the untreated Texin specimen exhibit both peak and residual loads that are intermediate in magnitude (Table 3, columns 2 and 3).

The fractions of residual load in relation to peak load are tabulated for each treated specimen after five minutes of stress-relaxation (Table 3, column 4). The ratio of peak load of each treated specimen to the peak load of the untreated specimen of the same product and the ratio of residual load of each treated specimen to residual load of the untreated specimen of the same product are also shown (Table 3, columns 5 and 6, respectively).

Discussion

Product and treatment comparison

The three untreated products behaved quite similarly in terms of their load onset and de-

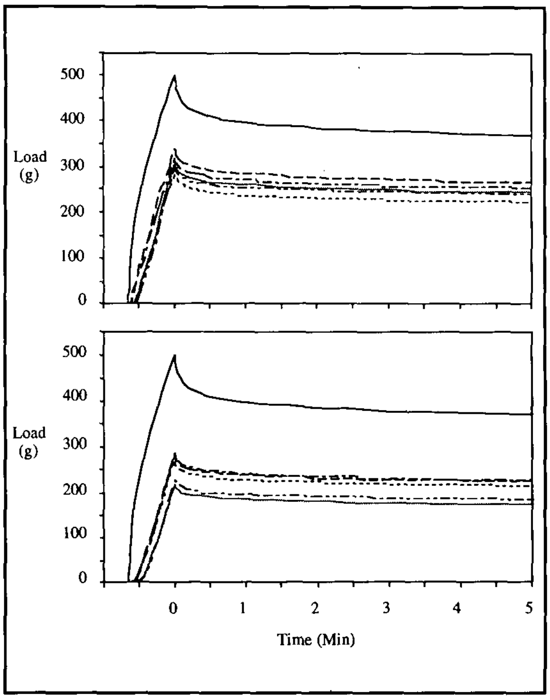

Figure 4A-B

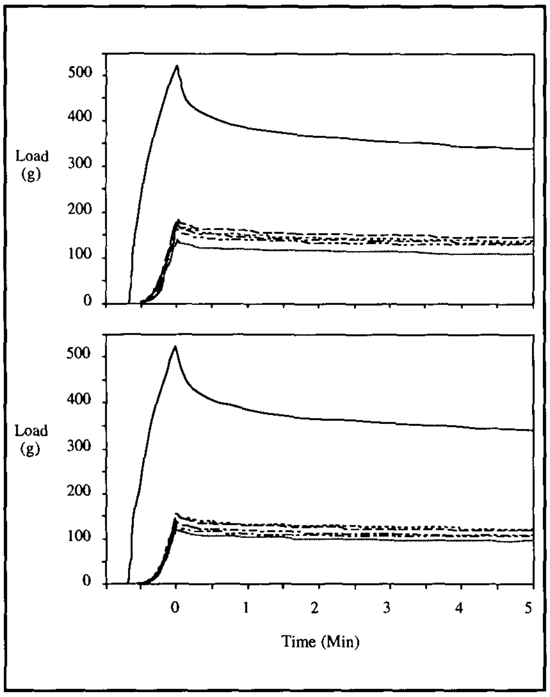

Figure 5A-B

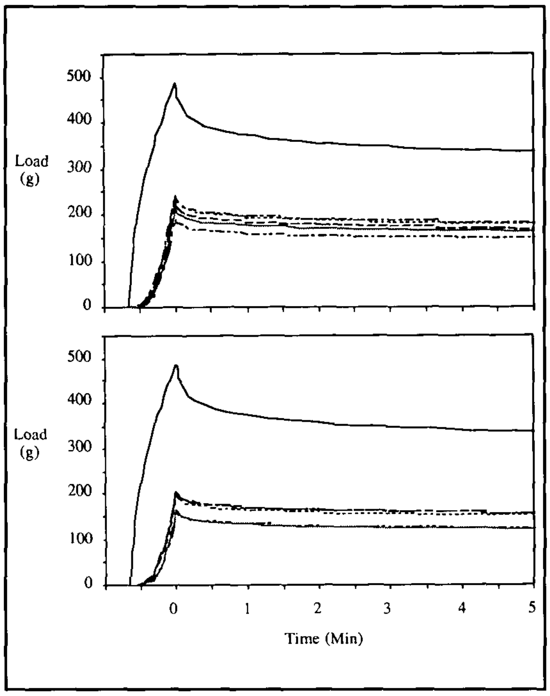

Figure 6A-B

Figure 4A-B
Load versus time curves for Nihon specimens that underwent treatments for 10 days (A) and 100 days (B). Specimens that underwent conditioning treatments 1, 2, 3, 4, and 5 are represented by the long dashes, the short dashes, the long with one short dash, the long with two short dashes, and the dotted line, respectively. The untreated control specimen of Nihon is identified by the solid line.

Figure 5A-B
Load versus time curves for Pellethane specimens that underwent treatment for 10 days (A) and 100 days (B). The line codes for conditioning treatments 0-5 are detailed in Figure 4.

Figure 6A-B
Load versus time curves for Texin specimens that underwent treatment for 10 days (A) and 100 days (B). The line codes for conditioning treatments 0-5 are detailed in Figure 4.

cay curves (Figure 3). With 74% residual load present after 5 minutes, the untreated non-prestressed Nihon chain displayed the greatest residual load (Table 3, column 4). Therefore, among the three untreated products evaluated, Nihon possessed the best load retention after activation. The Pellethane specimen displayed the largest peak load of 525 grams at the maximum displacement of 2.0 cm (Table 3, column 2), indicating that untreated Pellethane was the stiffest among the three untreated products studied.

Variations in conditioning treatments apparently affected the magnitude of residual load after relaxation (Table 3, column 3). However, the largest decreases were attributable to prestressing during treatment. Residual loads for the untreated, non-prestressed specimens equaled approximately 350 grams after 5 minutes; the treated specimens decayed to as little as 100 grams. Untreated specimens decayed more relative to their peak loads than did the treated specimens as can be seen by their residual load ratios (Table 3, column 4).

Stress-relaxation evaluation indicates that, among specimens that underwent any of the single-variable conditions (i.e., conditioning treatments 2, 3, or 4), those that underwent conditioning treatment 4 had the smallest peak load and residual load after 100 days ($p<0.001$). Thus, among the three variables studied (Table 2), an increase in temperature appeared the dominant single factor in the degradation mechanism responsible for the deterioration of the mechanical properties of these three products (Figures 4 to 6 and Table 3). No further significant change was obtained through conditioning treatment 5, which indicated that a combination of increases in acidity, oxygen content, and temperature had no synergistic effect on the stress-relaxation properties of the specimens compared with temperature alone.

Conditioning-treatment duration also af-

Figure 7
Given a constant deflection rate (top), typical force onset curves are shown (middle) for a viscoelastic material (solid line), an elastic material (long dashed line), and an elastomeric material (short dashed line). Also shown is the single-element Maxwell model of a viscoelastic material (bottom) in which K is the stiffness of the spring, r is the coefficient of resistance of the dashpot, and F is the force acting on the system.

Figure 8
Maxwell-Weichert model of a viscoelastic material (top) in which two Maxwell elements are connected in parallel and subjected to a common deflection. K_1 and K_2 are the stiffnesses of the first and second springs, respectively, r_1 and r_2 are the coefficients of resistance of the first and second dashpots, respectively, and F is the force acting on the system. For a constant deflection with time (middle) the stress-relaxation behavior of a two-element Maxwell-Weichert model equals the sum of the loads (F(t)) on the two elements as a function of time (t) in which x_0 is the constant elongation and $\tau_1(=r_1/K_1)$ and $\tau_2(=r_2/K_2)$ are the relaxation times for each element.

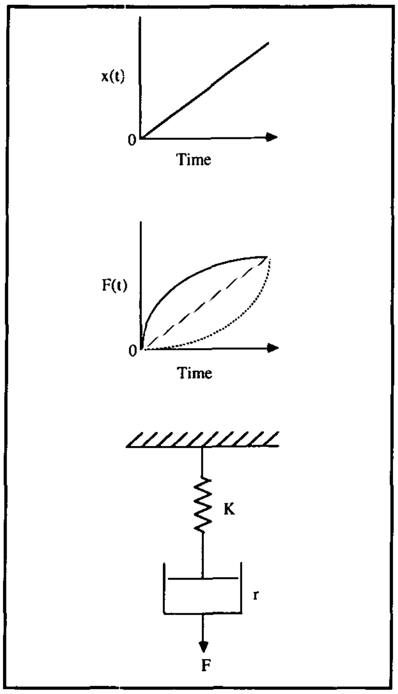

Figure 7

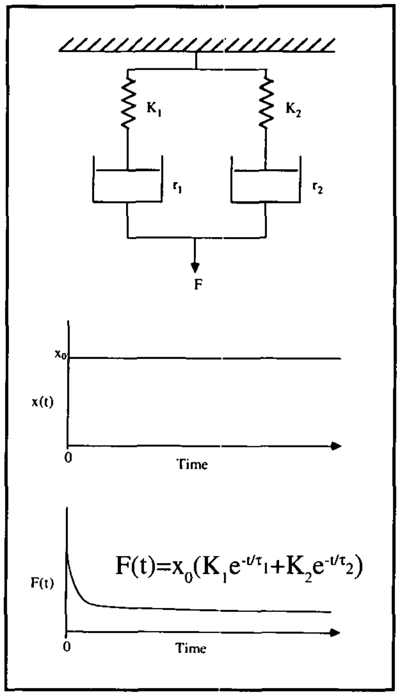

Figure 8

fected stress-relaxation properties. Peak and residual loads were less after 100-day treatments than after 10-day treatments for all three products ($p<0.001$) (Table 3, columns 2 and 3).

Finally, the product was a factor in peak and residual load values. All three products had significantly different load values after conditioning treatments. Nihon specimens had the largest values for peak and residual loads, followed by the Texin specimens and the Pellethane specimens ($p<0.001$), in both absolute (Table 3, columns 2 and 3) and relative terms (Table 3, columns 5 and 6).

Behavior modeling of load onset curves

Load-onset portions (to 0 min) of the stress-relaxation curves from the untreated specimens of all three products (Figure 3) exhibited responses that are characteristic of a single-element viscoelastic Maxwell model undergoing a constant deflection rate[8] (Figure 7, top and Figure 7, middle, solid line). That model consists of a viscous component (dashpot) and a linear elastic component (spring) in series[9] (Figure 7, bottom).

In contrast, the J-type load onset curves for the treated Pellethane and Texin products (Figures 5 and 6) were typical for elastomeric materials[10] (Figure 7, middle, dotted line) and showed the elastic-stretch mechanism. First, a gradual slope region was observed that resulted from the applied load, causing the individual entangled polymer molecules to uncoil. This uncoiling required little force because only weak secondary bonds were being broken within molecules. The steeper slope region corresponded to the reversible extension of straightened molecules—vis-a-vis elastic stretch. This mechanism requires greater force because primary covalent bonds were being stretched. Peak loads (nominally 125 to 225 grams, Table 3, column 2) from all Pellethane and Texin treated specimens were not great enough to cause chain slippage— a phenomenon in which a load increase causes the polymer molecules to slide past one another, thereby resulting in permanent deformation. Load onset curves for the treated Nihon products (Figure 4) were linear and exhibited reversible extensibility, as is characteristic of a classic elastic material (Figure 7, middle, dashed line).

Behavior modeling of force decay curves

Force decay curves from all untreated and treated specimens resemble the classic curves that are typical of a Maxwell model.[11]

$$F(t)=Kx_0^{-t/\tau} \qquad \text{(eqn 1)}$$

In this first-order exponential, F(t) is the load on the system as a function of time (t), K is the stiffness of the spring, x_0 is the constant elongation, and $\tau=r/K$ is the relaxation time for the system, in which r equals the coefficient of resistance of the dashpot.[12] Unfortunately, no values for K and τ could be found that pro-

Table 4
Force decay coefficients for two-element Maxwell-Weichert models of present work

Product/ treatment		K1 (g/cm)*	r1 (g•min/cm)**	Tau 1 (min)***	K2 (g/cm)*	r2 (g•min/cm)**	Tau 2 (min)***
Nihon							
0 day#	0	79.8	12	0.15	340	18700	55
10 days##	1	63.0	10	0.16	360	22700	62
	2	54.7	9.0	0.16	300	19500	65
	3	57.1	9.3	0.16	340	22900	67
	4	50.9	8.5	0.17	320	22100	68
	5	60.0	9.7	0.16	330	21300	64
100 days##	1	46.0	7.8	0.17	300	19700	65
	2	44.0	7.5	0.17	290	19400	67
	3	50.4	8.4	0.17	300	20000	66
	4	37.8	6.6	0.18	250	16100	65
	5	36.6	6.5	0.18	230	14500	62
Pellethane							
0 day#	0	106.1	15	0.14	330	10800	33
10 days##	1	31.1	5.6	0.18	200	9200	45
	2	31.0	5.6	0.18	190	8500	44
	3	30.0	5.5	0.18	190	7900	42
	4	26.6	5.0	0.19	180	9000	51
	5	22.9	4.4	0.19	150	8400	55
100 days##	1	25.0	5.0	0.20	170	7300	43
	2	25.3	4.8	0.19	170	8500	50
	3	21.5	4.2	0.19	150	6900	45
	4	20.2	4.0	0.20	140	8600	60
	5	18.6	3.7	0.20	130	5900	44
Texin							
0 day#	0	83.1	12	0.14	320	11800	37
10 days##	1	42.5	7.3	0.17	240	10800	46
	2	48.3	8.1	0.17	250	11900	48
	3	48.0	8.1	0.17	250	12700	51
	4	34.6	6.2	0.18	200	11600	57
	5	40.4	7.0	0.17	230	10900	48
100 days##	1	37.9	6.6	0.18	220	10800	50
	2	39.6	6.9	0.17	210	11300	54
	3	39.6	6.9	0.17	220	12400	57
	4	30.8	5.6	0.18	170	8000	47
	5	30.7	5.6	0.18	170	8300	49

* K1, K2= stiffnesses of the first and second springs, respectively.

** r1, r2= coefficients of resistance of the first and second dashpots, respectively.

*** Tau 1, Tau 2=relaxation times for the initial and secondary force decays, respectively. Tau=r/K.

x_0= 1.2 cm, since these were not prestressed before elongating them from 0.8 to 2.0 cm.

x_0= 0.8 cm, since these were prestressed. The permanent sets, which nominally equaled1.2 cm, were found to differ slightly from one another before elongating them from 1.2 to 2.0 cm.

vided a match for the load at the beginning of decay as well as for the load after longer times. Consequently, a Maxwell-Weichert model was considered that incorporates two Maxwell elements joined in parallel[8,13] (Figure 8, top).

$$F(t)=x_0(K_1e^{-t/\tau_1}+K_2e^{-t/\tau_2}) \quad \text{(eqn 2)}$$

For a constant deflection with time (Figure 8, middle), the values for K and τ can be determined both for a Maxwell element that governs initial decay and for a second Maxwell element that governs decay after longer times. The force decay curves for each Maxwell element are summed (Figure 8, bottom) to obtain the overall force decay curve of best fit.

Force decay curves for all untreated and treated specimens were fitted to the two-element Maxwell-Weichert model through calcu-

Figure 9
Force decay curves are compared for the untreated Nihon specimen (solid line) and its ideal Maxwell-Weichert model (dotted line). Individual force decay curves are shown for each of the two Maxwell elements (long and short dashed lines).

Figure 10
Force decay curves are compared for the Ormco Power Chain II as reported by Brantley et al.[6] (solid line) and its Maxwell-Weichert model (dashed line).

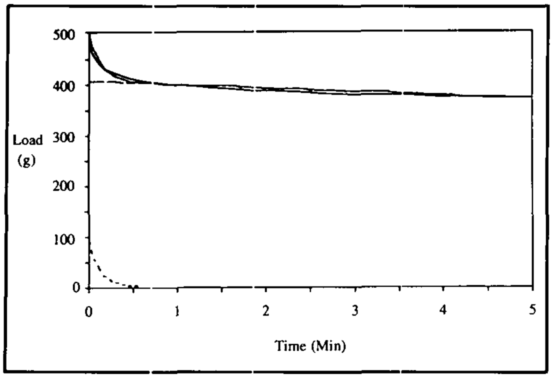

Figure 9

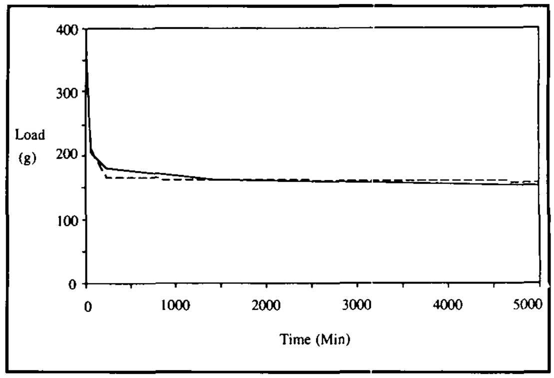

Figure 10

lation of values for K, r, and τ for both Maxwell elements (Table 4). Values of x_0 equaled 1.2 cm for all specimens that underwent conditioning treatment 0, whereas x_0 nominally equaled 0.8 cm for conditioning treatments 1 to 5. The force decay curve for the untreated Nihon specimen is compared with the force decay curve of its ideal Maxwell-Weichert model (Figure 9). For most specimens, the stiffnesses of both spring components decreased after 10-day and again after 100-day conditioning treatments (Table 4, columns 2 and 5). These observed trends in spring stiffnesses indicate that conditioning treatments decrease the elasticity of polyurethane elastomers. Coefficients of resistance of the initial dashpot components decreased for all specimens after 10-day and again after 100-day conditioning treatments (Table 4, column 3), but the Pellethane specimens displayed the only consistent decreasing trend for the coefficients of resistance of the second dashpot (Table 4, column 6). Initial relaxation times did not change significantly after conditioning treatments (Table 4, column 4), but relaxation times for the second Maxwell element substantially increased for all specimens after conditioning treatments (Table 4, column 7), supporting the theory that elasticity is decreased by conditioning treatments.

Comparison with literature

Behavior of other orthodontic elastomers can be modeled and predicted using the two-element Maxwell-Weichert model. In articles by Brantley et al.,[6] Wong,[2] and Bishara and Andreasen,[4] load values were observed for orthodontic elastics undergoing stress-relaxation. Using these results, the values for K, r, and τ were optimized for the two-element model by minimizing the residual error, i.e., the sum of the squares of the differences between the observed and calculated load values at each time interval (Table 5). Although these values differ in magnitude from those in the present study due to factors which include differences in product shape and/or size, relaxation duration, extension speed during load onset, and prestressing methods,[14,15] suitable force decay curves can be obtained for each product, an example of which is exhibited for the Power Chain II (Ormco Corporation, Glendora, Calif) studied by Brantley et al.[6] (Figure 10). A comparison of the observed results of earlier work to the calculated values "[ ]" for the present two-element model (Table 6) are generally in good agreement. Occasionally, a third Maxwell element might improve a fit (e.g., the second data set of Bishara and Andreasen[4]), but at the expense of increased computational time.

Clinical importance

Through the use of a Maxwell-Weichert model, which consists of a Maxwell element governing initial decay in parallel with a Maxwell element governing secondary decay, the orthodontist can predict load magnitude of elastomeric chains at activation and at any point during patient treatment. For example, if a Pellethane chain is used to close a diastema of a specified size, the orthodontist can calculate the load magnitude of the chain after any time by substituting the parameters for the untreated Pellethane (cf Table 4) along with its constant elongation (x_0) into eqn. (2). Moreover, if future values for K_1, K_2, τ_1 and τ_2 are measured for other products, then their force decay curves could also be predicted for a given x_0.

Because the largest portion of load decay begins immediately after load application, orthodontic manufacturers— or orthodontists themselves, particularly if elastic recovery occurs after such a short time interval— may find it beneficial to prestress all elastomeric chains to a 50% increase in length for one minute. This would allow the initial rapid decay (rep-

Table 5
Force decay coefficients for two-element Maxwell-Weichert models of earlier work

Author and reference	Product	K1(g/cm)	r1(g•min/cm)	Tau 1(min)	K2(g/cm)	r2(g•min/cm)	Tau 2 (min)
Brantley et al[6]*	Ormco Power Chain II	183	6.41×10^3	35.0	150	1.80×10^7	1.20×10^5
Brantley et al[6]*	Alastik C Spool Chain	237	8.53×10^3	36.0	141	1.28×10^7	9.10×10^4
Wong[2]**	Ormco Power Chain	289	2.60 x 10^5	900.0	173	17.3×10^9	1.00×10^8
Bishara & Andreasen[4]#	K1 Standard Alastik	254	7.11×10^2	2.8	426	3.02×10^7	7.10×10^4
Bishara & Andreasen[4]##	K1 Standard Alastik	266	4.52×10^2	1.7	202	2.16×10^7	1.07×10^5

* x_0=1.12 cm based on the fact that each chain, which contained four modules, was elongated 100% to 2.24 cm.

** x_0=0.74 cm based on a known elongation to 1.7 cm and the original doubleloop chain length of 0.96 cm, which was calculated from the measured elastic modulus of 460 g/cm.

\# x_0=0.7 cm based on a known elongation that started at an average length of 1.5 cm and ended at a length of 2.2 cm.

\## x_0=2.5 cm based on a known elongation that started at an average length of 1.5 cm and ended at a length of 4.0 cm.

Table 6
Comparison of the observed forces (g) from earlier work to the calculated forces"[ ]" for the two-element Maxwell-Weichert model

Author and reference		Time							
(cf Table 5)	Product	0	1 min	1 hr	4 hrs	1 day	1 wk	2 wks	3 wks
Brantley et al[6]	Ormco Power Chain II	374 [374]	* [368]	205 [205]	181 [168]	164 [167]	144 [155]	132 [142]	131 [131]
Brantley et al[6]	Alastik C Spool Chain	423 [423]	* [416]	208 [208]	178 [157]	147 [155]	125 [141]	116 [126]	113 [113]
Wong[2]	Ormco Power Chain	342 [342]	* [342]	* [328]	* [292]	171 [171]	128 [128]	* [128]	128 [128]
Bishara and Andreasen[4]	K1 Standard Alastik	476 [476]	422 [423]	311 [298]	* [298]	285 [293]	246 [259]	234 [225]	195 [195]
Bishara and Andreasen[4]	K1 Standard Alastik	1170 [1170]	872 [874]	577 [504]	* [503]	462 [497]	425 [459]	354 [418]	380 [380]

* No observed results were tabulated for this time by the investigators.

resented by the first Maxwell element) to occur before placement of the chain. In this way, the magnitude of applied load would be only that required for the desired tooth movement (represented by the second Maxwell element), and patient discomfort due to excessive load at insertion would be minimized.

Conclusions

1. Among the variables studied (acidity, oxygen content, and temperature), an increase in temperature appears to be the dominant single factor in the degradation mechanism responsible for the deterioration of the mechanical properties of polyurethane elastomeric materials. Synergism plays no significant role.

2. Prestressing during conditioning treatments has a larger deteriorative effect than any

of the conditioning treatments. Therefore, prestressing elastomeric orthodontic chains may lessen force degradation after placement, increasing their effectiveness as a tooth-moving mechanism.

3. Load-onset portions of the stress-relaxation curves from all untreated specimens exhibited responses characteristic of viscoelastic single-element Maxwell models undergoing constant deflection rates. Load-onset curves for the treated Pellethane and Texin specimens were characteristic of elastomeric materials; the load-onset curves for the treated Nihon specimens were characteristic of elastic materials.

4. All untreated and treated specimens displayed exponential force-decay curves that could be represented by a Maxwell-Weichert model consisting of a Maxwell element governing initial decay in parallel with a second Maxwell element governing decay after longer times. Through the use of this model, loads can be estimated from force-decay curves of elastomeric chains, thereby enabling the orthodontist to anticipate whether the patient will experience any discomfort upon insertion and whether the appliance will be effective after a prescribed time.

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Author Address

Dr. Robert P. Kusy
Dental Research Center
CB #7455
University of North Carolina
Chapel Hill, NC 27599

R.P. Kusy, Department of Biomedical Engineering and Department of Orthodontics, University of North Carolina, Chapel Hill.

J.S. Stevenson, formerly Department of Biomedical Engineering, presently Engineer of Fiber Manufacturing at Litespec, Inc., Research Triangle Park, NC.

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Commentary: Characteristics of elastomeric chains

Sunil Kapila, DDS, MS, PhD

The application of mechanical forces which produce optimal rates of tooth movement within the "physiologically tolerable" limits of the tissues remains of primary importance to the practice of orthodontics. To this end, several force-generating materials and auxiliaries are currently used in orthodontics. Elastomeric chains are a popular option. Despite the common use of these auxiliaries for purposes of space consolidation and tooth movement, a comprehensive understanding of their mechanical characteristics is far from complete. Knowledge of the potential clinical performance of these force-generating elements of an appliance can be gained from sound scientific investigation. The present study makes an important contribution to this area.

This investigators evaluated the in vitro stress-relaxation characteristics of three polyurethane-based elastomeric chains subjected to prestressing and variations in environmental pH, oxygen concentration, and temperature for periods of 10 or 100 days. Stress-relaxation is the force decay over time exhibited by a material maintained under constant strain. The stress-relaxation characteristics of an elastomeric chain, therefore, provide an assessment of potential clinical behavior by defining the force magnitudes placed on teeth as the chain "relaxes." The findings demonstrate that prestressing as well as temperature significantly affect the peak and residual loads of elastomeric chains, while oxygen concentration and change in pH have no significant effects on these characteristics of the elastomers. The study also demonstrates slightly different stress-relaxation characteristics of three elastomeric chains tested, although the significance of these small differences is questionable.

This study, while using some previously applied methods for evaluating the stress-relaxation characteristics of elastomers and confirming previous findings of the effects of prestressing, has gone further by using the data to derive clinically useful formulations. A Maxwell-Weichert model consisting of springs and dashpots, which may enable the clinician to predict the load magnitudes applied by the elastomers during treatment, was determined for this purpose. It is likely that further development and refinement of these approaches for calculating force levels, together with an increased ease in clinical applicability of such formulas may eventually provide a useful aid in more accurately determining force levels during orthodontic mechanotherapy.

With respect to the experimental design, the rationale for placing the elastomeric chains in phosphate buffered solution at pH and temperature approximating that of the mouth during prestressing is not quite clear. This approach gives the impression that the elastomers were being prestressed while in a simulated oral environment. Therefore, an alternative interpretation of the experimental design and results is to consider the treatments as exposing the elastomers to one or more variables of a simulated oral environment. In such a scenario, the phosphate buffered solution may represent saliva incorporating alterations in other variables such as its pH and temperature. Stretching the three loops of the elastomeric chains on the stainless steel rods may appear to represent the placement of loops on brackets with one exception: the interloop segments were not stressed. The evaluation of stress-relaxation characteristics following these treatments may then indicate the characteristics of the elastomers following exposure to a simulated clinical environment for 10 to 100 days, although the latter period of exposure may not be clinically relevant since elastomeric chains are rarely left in situ for such extended periods of time. With such an interpretation of the experimental design, it becomes obvious that the effects of stressing an elastomeric chain, such as when placing it on a bracket, introduces a permanent set of approximately 50% in the elastomer and significantly decreases its peak and residual force levels during stress-relaxation experiments. These changes in stress-relaxation characteristics may then have substantial consequences for the ability of the chains to initiate and maintain optimal rates of tooth movement. Although this change in premise does not diminish the validity of the findings, it provides a different perspective. It indicates that exposure of elastomeric chains to a simulated oral environment substantially alters their stress-relaxation characteristics which are attributable largely to the stressing and temperature treatments.

Further examination of the experimental design also reveals that, although various treatments do produce significant differences in stress-relaxation characteristics of the elastomers, the sample size of one in each cell is minimal. An increased sample size would add to the validity of the statistical analyses and provide an assessment of the variability in stress-relaxation characteristics of the elastomeric chains associated with the manufacturing processes and those resulting subsequent to the treatments. This information may be important in explaining any variabilities in the clinical performance of these elastomers.

As a final thought, although prestressing decreases the force degradation of elastomeric chains, which may be beneficial in providing near-continuous forces, an important question remains as to whether the force levels left after stressing are adequate to initiate or maintain tooth movement. In this context, at least other important variables need to be taken into account. The first relates to what proportion of the force applied by the elastomeric chain is required to overcome bracket-wire frictional forces. If this is substantial, then the residual forces transmitted to the periodontal tissues may not be sufficient to induce biologic responses leading to tooth movement. The second variable is the force magnitudes required to cause bone remodeling and subsequent tooth movement. Although some recent evidence indicates that both the magnitude and frequency of forces required to maintain or add mineralized tissue to bone may be minimal,[1-4] little such information from well controlled studies on orthodontic tooth movement is currently available. Certainly, studies that evaluate which levels of applied forces are actually transmitted to tissues and cells of the periodontal ligament, and those that evaluate optimal forces required to cause biologic tissue responses are highly desirable in order to provide a stronger scientific basis for the practice of orthodontics. With such information it may be possible, for example, to determine whether the initial level of forces from elastomeric chains far exceed those required to cause tooth movement, and which, because of their rapid force decay, quickly drop below optimal levels for tooth movement. This knowledge may lead to the development of new materials and techniques which permit efficient, effective and "physiologic" tooth movement throughout the period between orthodontic visits.

S. Kapila is an assistant professor in the Department of Growth and Development, University of California, San Francisco.

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