Viscoelastic properties of an aesthetic translucent orthodontic wire

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SUMMARY The objective of this study was to evaluate the time-dependent viscoelastic properties of an aesthetic orthodontic archwire. The wire is based on a recently developed translucent polyphenylene thermoplastic, whose rigid molecular structure provides high strength. While the wire has good instantaneous mechanical properties, over time all polymers may relax so it is important to understand the potential impact of the relaxation on orthodontic force systems.

Four samples of 0.020 inch round and six samples of 0.021 × 0.025 inch rectangular wire were loaded in tension to a range of initial stresses, and relaxation of the stress was monitored for 7 days. Sixty-three additional samples were maintained in edgewise bracket pairs with vertical displacement for up to 6 weeks. The deformation of these wires was measured immediately after removal from the brackets and for 2 days as the samples recovered.

Tensile stress decayed about 10–30 per cent over 24–48 hours depending on the initial stress. The relaxation behaviour was proportional to the initial tensile strain and therefore these data were combined into a single curve using regression. Deformation of the samples placed in the bracket pairs increased with increasing vertical displacement and time, evaluated with analysis of variance, but 19–100 per cent of the deformation was recoverable.

The force systems from polyphenylene wires could vary with time and activation, but this behaviour is predictable.

Introduction

Increasing interest in aesthetic orthodontic appliances using labially placed brackets and wires led to the development of ceramic brackets. The latest development is a translucent all-polymeric wire with high springback and high ductility (Goldberg and Burstone, 2007; Burstone *et al.*, 2010). The wire is based on polyphenylene, a novel polymer whose rigid molecular structure leads to a high yield strength and modulus of elasticity (Marrocco *et al.*, 2000). This class of material is also referred to as self-reinforcing polymer (SRP). Because the high mechanical properties are achieved without fibres, the wire has good ductility allowing placement of bends. A preliminary clinical evaluation of SRP archwires confirmed the efficiency of tooth movement during the initial or levelling phase of treatment (Kuhlberg, 2009). The major instantaneous mechanical properties of the archwires, including the yield strength, modulus, and percentage elongation, have been determined (Burstone *et al.*, 2010). However, since the mechanical properties of polymers are time dependent, it is necessary to evaluate this characteristic and determine its impact under clinically relevant loading conditions.

The field of orthodontics is familiar with the concept of time-dependent or viscoelastic mechanical response with both appliances and tissues. Orthodontic elastics (Gioka *et al.*, 2006) and polymeric chain modules (McKamey *et al.*, 2000) exhibit an instantaneous response to elongation, then the force decays at a decreasing rate over time. This pattern is shown schematically in Figure 1A and is associated with time-dependent conformational changes in the polymer chains (Eliades *et al.*, 1999). A polymeric ligature has been characterized that shows similar behaviour and the results followed a standard load-decay curve similar to Figure 1A (McKamey and Kusy, 1999). Detailed discussions of viscoelasticity of polymers can be found elsewhere (Alfrey, 1948; Ferry, 1980). Fibre-reinforced composite archwires may show stress relaxation (Zufall and Kusy, 2000). Any time-dependent relaxation of solid metal orthodontic wire is generally not considered clinically significant. Finally, the periodontal ligament (PDL) also displays viscoelastic properties when measured *in vitro* (Dorow *et al.*, 2003) and during orthodontic treatment (Anastasi *et al.*, 2008).

When a metal wire or spring is inserted into brackets on malaligned teeth, the teeth instantaneously displace a small amount due to strain in the PDL. Then, over time, the applied forces decrease only as the teeth move, associated with biological strain changes that reduce the wire activation. During non-moving intervals, the force and strain in metal appliances remain constant. Additionally,
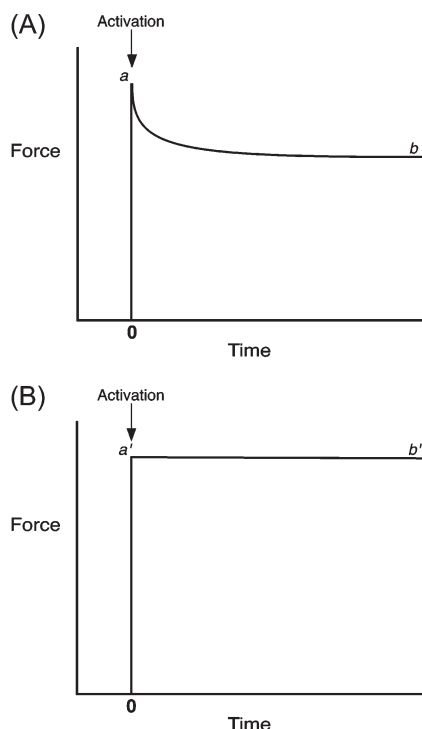
Figure 1 Idealized pattern of changes in force with a constant activation for (A) an amorphous polymer wire experiencing stress relaxation and (B) a traditional metal wire where the force remains constant. For polymers, with time, there is a gradual decrease in force.

after initial activation, the deformation in the metal does not change over time. The constant wire deformation over time and lack of force loss if appliance activation does not change facilitate more accurate prediction of force systems in a metal orthodontic appliance. Polymeric wires, on the other hand, bring a new paradigm to orthodontic archwire biomechanics. Use of polymers will require an understanding of their time-dependent characteristics, concepts not necessary to consider with traditional metal appliances.

When a polymeric wire is activated, there is an instantaneous applied force proportional to the activation, which is represented by position *a* in Figure 1A. This is the same as found with metal wires, represented by position *a'* in Figure 1B. However, for polymers, with time, the extended molecular conformations relax towards their equilibrium position causing a gradual decrease in the applied force even though the deflection (activation) is constant, represented by segment *ab* in Figure 1A. This is referred to as stress relaxation. In metals, the force remains constant with a constant activation, represented by segment *a'b'* in Figure 1B. Clinically, such behaviour in a polymeric wire would be acceptable for orthodontic force systems as long as the relaxation is modest relative to total stress. It may also be acceptable if the behaviour is predictable so the orthodontist can compensate by appliance design or activation. Using instantaneous loading alone to determine material properties of a polymeric orthodontic wire may not

accurately reflect the actual delivered forces or the observed deformation under clinical conditions.

The aim of this research was to characterize the clinically relevant stress relaxation and deformation properties of polyphenylene SRP orthodontic wires. While these wires provide the potential advantages of aesthetics and formability, a clinician would need to understand the instantaneous and time-dependent characteristics, broadly referred to as viscoelastic properties.

Materials and methods

The orthodontic wires used in this study were polyphenylene-based SRPs (Marrocco *et al.*, 2000). The chemical structure and instantaneous mechanical properties (modulus, strength, and formability) of wires formed from the polymer have been described earlier (Burstone *et al.*, 2010).

Stress relaxation in tension

Starting with polyphenylene-based pellets (PR-250; Solvay Advanced Polymers, LLC, Alpharetta, Georgia, USA), round and rectangular wires with nominal cross sections of 0.020 inch and 0.021 × 0.025 inch, respectively, were produced by Zeus Industrial Products, Inc. (Orangeburg, South Carolina, USA). Approximately 100 feet of each cross-sectional size was extruded. Four round and six rectangular samples, each approximately 27.5 inches (70 cm) in length, were loaded in tension in a universal testing machine (Instron, Model 3343, Norwood, Massachusetts, USA). A 1 inch strain gauge extensometer was carefully attached and the samples were loaded at a rate of 5 mm/minute. The four round samples were loaded until reaching 20, 40, 60, and 80 per cent of the yield stress, which was previously determined to be 105.9 MPa for this batch. The six rectangular samples were loaded to 20, 40, 60, 80, 90, and 95 per cent of the yield stress, which was 104.2 MPa. The extension (strain) was held constant and the decreasing stress (stress relaxation) was continuously monitored for up to 7 days. The tests with rectangular wire at 20 and 40 per cent of yield stress were stopped at approximately 90 hours when there was no further decrease in stress. The remaining eight samples were monitored for 7 days even if the stresses remained constant.

Deformation and recovery in flexure

Sets of edgewise bracket pairs (Mini Diamond Twin, lateral incisor, 0.022 inch slot, 3.1 mm width, 0 degree torque, 0 degree angle, #531-0204; Ormco, Orange, California, USA) with an inter-bracket distance of 7 mm and vertical displacements of 1, 2, and 3 mm were bonded with self-curing cyanoacrylate adhesive (Krazy Glue; Elmer's Products, Columbus, Ohio, USA) to acrylic sheets (Figure 2). Samples of both the 0.020 inch round and 0.021 × 0.025 inch rectangular polyphenylene wire were secured within each pair of brackets with an elastic 'O' ring and held in

place for 24 hours, 1, 2, 3, 4, 5, and 6 weeks. The samples were then released from the second bracket and deformation was measured as the difference in vertical displacement between the wire and the first bracket. Deformation was measured at 10 seconds (hereafter referred to as 'immediate' or 'instantaneous'), 1 minute, 1 hour, 1 day, and 2 days after release from the second bracket. Displacement was measured with a grid that allowed reading to the nearest 0.25 mm. Three samples were evaluated for each of the three vertical displacements and seven time periods. The instantaneous deformation after being held in the brackets for 3 and 6 weeks was compared across the three vertical displacements of 1, 2, and 3 mm with two-way analysis of variance. The tests of the bracket pairs and the stress relaxation tests in tension were conducted at an ambient laboratory temperature of $20 \pm 2\degree C$.

Results

Stress relaxation in tension

The decrease in stress while being held at a constant strain exhibited classic polymeric viscoelastic behaviour (Figure 3). The rate of relaxation decreased over the first 24–48 hours, then asymptotically approached a constant value. The magnitude of the relaxation increased with increasing initial stress, with wires maintaining 61.3–89.9 per cent of the original stress (Table 1). The time period for the time-dependent response increased with initial stress level from a few hours for wires loaded to 20 per cent of the yield strength to about 50 hours for the sample loaded to 95 per cent of the yield strength.

The stress at each point in time was proportional to the applied strain (Figure 3A and 3B). Polymers that exhibit this behaviour are referred to as linearly viscoelastic and allow all the data to be combined into one universal stress-decay curve. The stress values for the eight round and rectangular samples in Figure 3 monitored for 7 days were divided by their corresponding constant strains (Table 1) and all data collapsed to the single curve shown in Figure 4. The solid line represents the mean stress/strain values and the dotted lines show the 95 per cent confidence limits determined with non-linear regression analysis (Prism 5; GraphPad Software, La Jolla, California, USA). The stress/strain values had a confidence range of about ±0.5 GPa. The viscoelastic
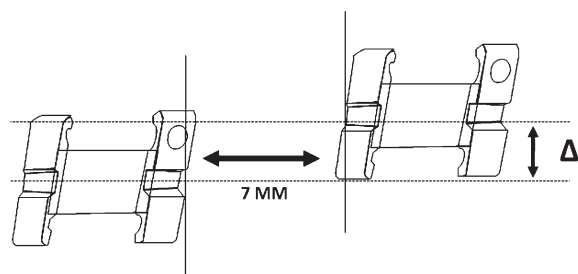

Figure 2 Schematic drawing of bracket pairs used to evaluate deformation and recovery. $\Delta = 1$, 2, or 3 mm.

behaviour was consistent with an earlier evaluation of SRP time-dependent properties (Dean *et al.*, 1998).

To further examine the relationship between initial applied stress and the percentage of stress retained, these parameters from Table 1 for round and rectangular wires were plotted (Figure 5). A linear regression of these data showed a very good fit with Pearson correlation coefficients, r^2, of 0.997 and 0.997 for the round and rectangular wire samples, respectively.

Deformation and recovery in flexure

The mean deformation of the round and rectangular wires immediately after removal from the bracket pairs is shown
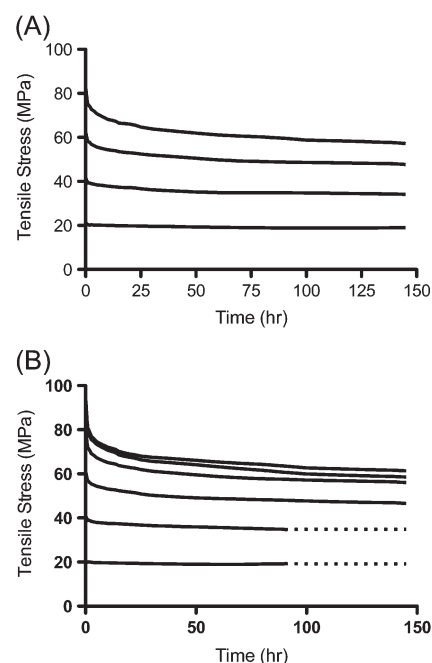

Figure 3 Stress relaxation in tension of polyphenylene wires while being maintained at various initial strain levels for the (A) 0.020 inch round and (B) 0.021 × 0.025 inch rectangular cross-section wires.

Table 1 Summary of stress relaxation results for round and rectangular wires.

Percentage of yield stress applied	Constant strain (%)	Initial stress (MPa)	Stress at 7 days (MPa)	Percentage of initial stress retained
Round				
20	0.360	21.2	18.4	87.0
40	0.720	42.4	33.9	80.0
60	1.080	63.6	46.9	73.8
80	1.440	84.7	55.7	65.7
Rectangular				
20	0.340	20.8	18.7	89.9
40	0.708	41.7	34.5	82.7
60	1.062	62.5	45.9	73.4
80	1.416	83.3	55.4	66.5
90	1.593	93.8	58.1	61.9
95	1.682	99.0	60.7	61.3

in Figure 6A and 6B, respectively. Separate plots are shown for the wires maintained at 1, 2, and 3 mm displacements for up to 6 weeks. The pattern is consistent with the viscoelastic behaviour observed in the tensile stress relaxation tests. For the round wires (Figure 6A), all three vertical displacements (1, 2, and 3 mm) caused an increase in the instantaneous deformation over approximately the first 3 weeks, followed by no further change ($P < 0.001$). The magnitude of the vertical displacement had a greater effect than time, with the 3 mm step causing an apparent deformation of about 1.3 mm after 6 weeks in the brackets. The 1 mm step caused an apparent deformation of about 0.3 mm after this time period. The pattern for the rectangular wires was similar (Figure 6B), although the increase in deformation from 3 to 6 weeks was statistically significant ($P < 0.003$).

Recovery, or the decrease in deformation with time after removal of the wires from the brackets, is shown in Figure 7. For brevity, only the results for the round and rectangular wires maintained in the brackets for 24 hours (Figure 7A and 7C) and 6 weeks (Figure 7B and 7D) are shown. All wires demonstrated decreased deformation (increased recovery) with time after release from the brackets.
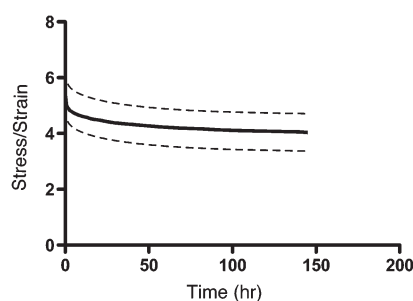

Figure 4 The mean (solid line) and 95 per cent confidence levels (dashed lines) for the relaxation modulus (stress/strain) for the eight round and rectangular samples in Figure 3 monitored for 7 days. By dividing the stress in each sample by its constant strain, all data from Figure 3 collapse to one common relaxation curve.
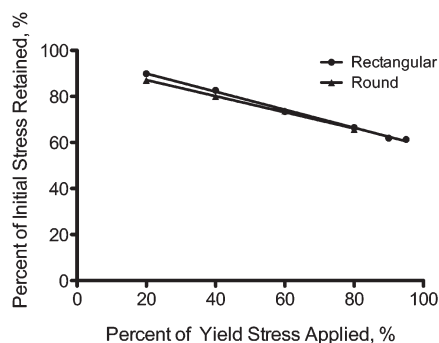

Figure 5 The percentage of the initial tensile stress retained versus the percentage of yield stress applied for both the 0.020 inch round and 0.021 × 0.025 inch rectangular polyphenylene wires.

Discussion

The results confirm that polyphenlene-based SRP orthodontic wires exhibit viscoelastic properties typical for an amorphous polymer. The viscoelastic behaviour is approximately linear, meaning the stress is proportional to the applied strain or deformation. The practical, clinical implications of viscoelasticity are discussed below by comparing these wires with traditional metals wires in a straight wire application at initial wire placement and during active tooth movement, with the wires loaded above and below their yield strengths. The main difference between polymeric and metal wires is the time-dependent response that will affect both the applied force and observed deformation.

In the initial placement of a metal wire, if the deflection is below the yield strength, no permanent deformation occurs either initially or over time. The force remains constant provided the deflection or activation does not change. For polymeric wires, initial placement with loading and deflection below the yield strength will result in no deformation initially, however, over time the force will decrease and deformation will increase. The magnitude of these effects is dependent on the force level and time. For the SRP wires tested in tension, the force decreased about 10–30 per cent depending on the initial force level over a
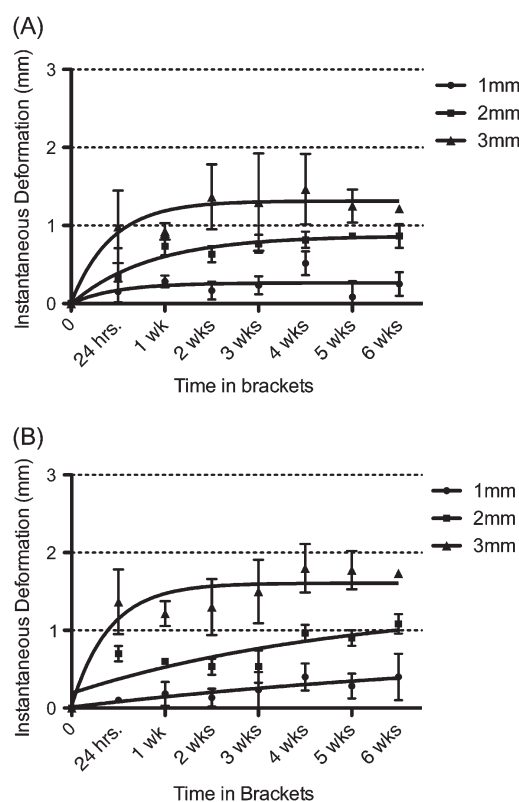

Figure 6 The deformation in wire samples immediately after being held in bracket pairs for up to 6 weeks with vertical displacements of 1, 2, and 3 mm. The mean and standard deviation is shown for each of the seven time points. The solid line is a regression fit to the means. (A) 0.020 inch round and (B) 0.021 × 0.025 inch rectangular wires.
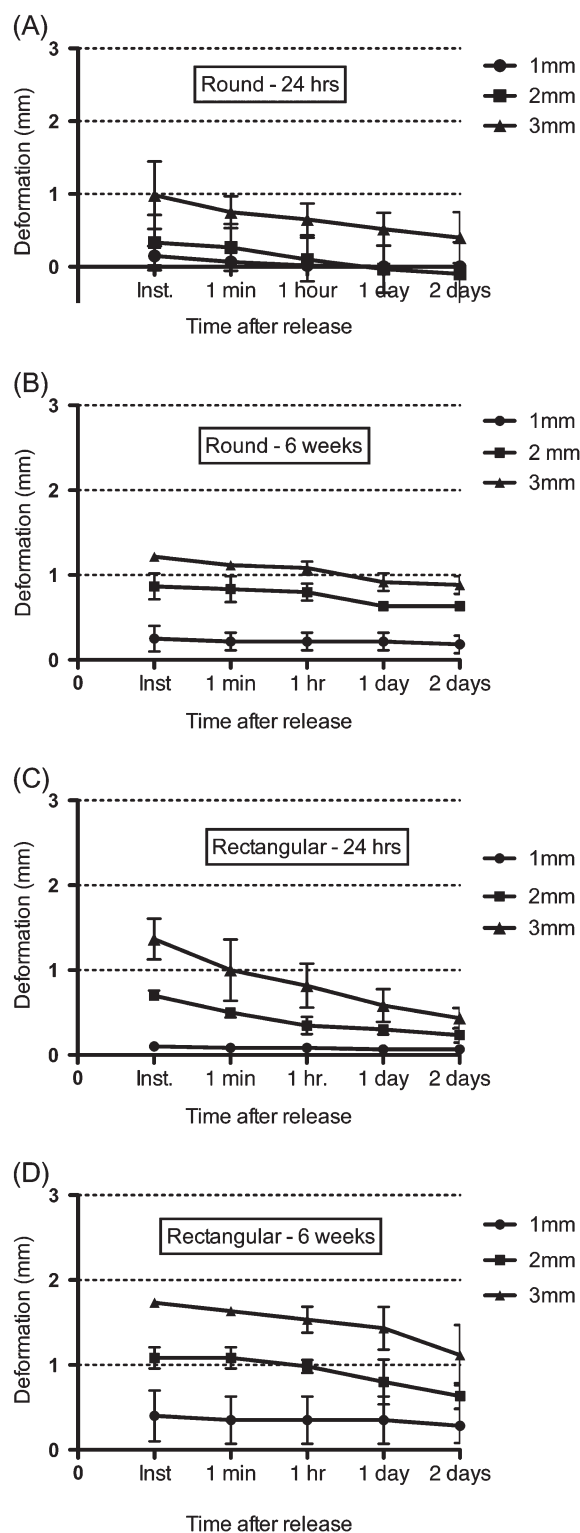
Figure 7 Recovery (decrease in deformation) of the polyphenylene wire samples after being held in the bracket pairs for 24 hours and 6 weeks with vertical displacements of 1, 2, and 3 mm. Means and standard deviations are shown. (A, B) 0.020 inch round wire cross section; (C, D) 0.021 × 0.025 inch rectangular wire cross section.

period of up to 48 hours. With loading below the yield strength, the increased deformation over time is 'apparent' since recovery can occur if the teeth move to a new position reducing the stress or after removal from the brackets given sufficient time before reinserting the archwire.

For initial placement with loading above the yield strength, metal wires display permanent deformation that will not change over time. The force present after bracket engagement will also remain constant (assuming no change in bracket positions). With the polymeric SRP wires, the force will again decrease over about 48 hours. The deformation will have a permanent component and a time-dependent recoverable component.

If the appliance is considered after the teeth have moved during alignment, then there is now less deflection. The metal wire will deliver less force, and if there was much permanent deformation, no force. The polymeric wire that exhibited a time-dependent force loss and deformation can recover part of the deformation and the force loss.

There is also a clinically observable difference in the deformation of metal and SRP wires. The deformation of a metal wire will be the same whether it is removed immediately after initial insertion or after a given time period, for example 6 weeks. If the SRP wire is removed immediately after insertion, it may show less deformation than after a longer time interval in the mouth. In other words, in this scenario not considering time-dependent effects enhances the apparent performance of the polymeric wire—it will exhibit higher springback. If the wire is removed after a longer time in the mouth, it might show additional deformation. This 'apparent' deformation might exaggerate the loss of spring back since a portion may be recoverable and hence, it should not be interpreted as strictly permanent 'deformation'. As an example from the present data (Figure 7D), a 0.021 × 0.025 inch rectangular wire maintained at a 3 mm deflection for 6 weeks will exhibit approximately 1.7 mm of deformation when initially removed from the brackets. However, over 2 days, the deformation reduces to approximately 1.0 mm. In this case, about 40 per cent of the deformation was recoverable and contributed to the applied force when in the brackets. This is recovery after all forces are removed and the wire is allowed to remain at room temperature (with some heating the recovery can be accelerated). This is relevant if the wire is then reinserted into the mouth since less deformation will be present than that observed immediately after wire removal. The more relevant clinical situation is where, under constant strain, the archwire overtime exhibits loss of force (stress relaxation). Then, as the teeth move to a new position, strain is reduced allowing possible recovery of part of the stress relaxation.

In addition to relaxation of the forces, time-dependent effects on deformation are of interest. During active appliance use, there should be no or little permanent deformation. If a bend (or twist) is placed or if the appliance is reformed in any way, the clinician would like the new shape to be permanent.

The time-dependent behaviour of the SRP wire should be considered when making a permanent shape change. As an example, if a 90 degree bend is placed in a polyphenylene SRP wire, some of the desired deformation is not permanent and will recover over time. This unintended straightening of the wire is accelerated by heat. To ensure that a bend placed in an appliance will not be negatively influenced by this recovery phenomenon, the wire should be over-bent and bent back to the desired shape. Over-bending followed by low temperature heating such as 60°C also will enhance shape stability. This final shape produced by a combination of low heat and/or over-bending is now resistant to undesirable time-dependent recovery and will be maintained during treatment.

The stress relaxation (Figures 3 and 4), increasing deformation (Figure 6), and recovery (Figure 7) are all a result of the time-dependent molecular rearrangement of the polymer chains. Therefore, it is not surprising that the mechanical response curves all have the same general shape, which is an exponential function. The details of this mathematical function can be found elsewhere (Alfrey, 1948; Ferry, 1980). The clinically relevant point is that the mechanical behaviour can be modelled and is predictable. For various round and rectangular wire cross sections, tables or graphs could be constructed to show the change in force and deformation over time. Furthermore, since polyphenylene SRP wires can be extruded and injection moulded a wide range of novel cross sections and spring designs are feasible and may be clinically useful. The forces and deformation of these more complex appliances could also be predicted over time based on the viscoelastic models shown here.

The mechanical properties of polymers, including viscoelasticity, are potentially dependent on temperature and moisture. Studies of similar polyphenylene polymers have demonstrated that the temperatures experienced in the mouth will have only a very modest effect on the polymer's mechanical properties in clinical use (Dean *et al.*, 1998). The moisture absorption of polyphenylene is 0.1 per cent (Solvay Advanced Polymers, 2008, Preliminary Data Sheet). Generally, this low amount of water absorption would not be expected to affect mechanical properties, particularly at mouth temperatures, but studies of this issue are in progress.

Conclusions

Unlike metal wires, polyphenylene SRP orthodontic wires exhibit time-dependent behaviour associated with viscoelastic properties, which result in the following clinical characteristics:

1. Forces that are applied below the yield strength can produce both stress relaxation (loss of force) and deformation. With reduction in wire strain as teeth move, some of the force loss and deformation is recoverable over time.

2. Instantaneous tensile and flexural tests that are adequate to define metal wire properties may be inadequate to define polymeric wires sufficiently to optimize their clinical use.

3. The viscoelastic behaviour is near linear, meaning that the stress relaxation or deformation are approximately proportional to the initial load or deflection and therefore predictable.

4. Large deflections approaching the yield strength can produce significant time-dependent force loss and deformation; these effects are insignificant in clinical applications using small deflections.

5. A desired bend or a twist placed in a wire by cold forming can lead to excessive permanent deformation during wire activation. Over time, the recoverable deformation component can spontaneously reduce the bend. Permanent deformation after activating a bend can be reduced by both over-bending and then bending back to the final shape along with a heat treatment.

6. The SRP aesthetic translucent polyphenylene arch requires the orthodontist to understand and apply important viscoelastic concepts to optimize its clinical use.

References

Alfrey T 1948 Mechanical behavior of high polymers. Interscience, New York

Anastasi G *et al.* 2008 An immunohistochemical, histological, and electron-microscopic study of the human periodontal ligament during orthodontic treatment. International Journal of Molecular Medicine 21: 545–554

Burstone C J, Liebler S A H, Goldberg A J 2010 Polyphenylene polymers as aesthetic orthodontic arch wires. American Journal of Orthodontics and Dentofacial Orthopedics. In Press

Dean D, Husband M, Trimmer M 1998 Time-temperature-dependent behavior of a substituted poly (paraphenylene): tensile, creep, and dynamic mechanical properties in the glassy state. Journal of Polymer Science B: Polymer Physics 70: 2971–2979

Dorow C, Krstin N, Sander F G 2003 Determination of the mechanical properties of the periodontal ligament in a uniaxial tensional experiment. Journal of Orofacial Orthopedics 64: 100–107

Eliades T, Eliades G, Watts D C 1999 Structural conformation of *in vitro* and *in vivo* aged orthodontic elastomeric modules. European Journal of Orthodontics 21: 649–658

Ferry J D 1980 Viscoelastic properties of polymers, 3rd edn. Wiley, New York

Gioka C, Zinelis S, Eliades T 2006 Orthodontic latex elastics: a force relaxation study. The Angle Orthodontist 76: 475–479

Goldberg A J, Burstone C J 2007 Advanced thermoplastics for orthodontics. US Patent 7,186,115

Kuhlberg A J 2009 Esthetic orthodontic wire clinical trial. New Ortho Polymers, Inc., Farmington

Marrocco M L, Gagne R R, Trimmer M S 2000 Rigid-rod polymers. US Patent 6,087,467

McKamey R P, Kusy R P 1999 Stress-relaxing composite ligature wires: formulations and characteristics. Angle Orthodontist 69: 441–449

McKamey R P, Whitley J Q, Kusy R P 2000 Physical and mechanical characteristics of a chlorine-substituted poly (para-xylylene) coating on orthodontic chain modules. Journal of Materials Science: Materials in Medicine 11: 407–419

Zufall S W, Kusy R P 2000 Stress relaxation and recovery behaviour of composite orthodontic archwires in bending. European Journal of Orthodontics 22: 1–12