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Investigation of Force Decay in Aesthetic, Fibre-Reinforced Composite Orthodontic Archwires

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Summary

Background/Objectives: Because polymer-based materials typically exhibit viscoelastic properties, the objective was to determine if commercially available, aesthetic, fibre-reinforced composite archwires maintain continuous forces without undergoing force decay when deflected continuously.

Materials/Methods: Quasi force decay was evaluated by comparing three-point bending profiles of nickel–titanium (NiTi) and fibre-reinforced composite archwires (BioMers) prior to and after 30 days of continuous deflection of either 1 or 2mm. Paired t-tests or non-parametric signed rank tests were used to statistically compare pre- and post-deflection bending forces. A control group consisting of wires not subject to the 30-day constant deflection was tested to check whether the initial testing altered the second three-point bend test.

Results: Significant ($P < 0.01$) differences in the pre- and post-deflection deactivation force delivery were most evident in the composite 2mm deflection group and all of the NiTi groups. The composite 2mm deflection group failed to deliver consistent forces as the majority of the wires experienced crazing during the 30-day deflection period. The decrease in force delivery in the NiTi groups may be attributed to the small standard deviations.

Conclusions: The composite 1mm deflection group demonstrated that fibre-reinforced composite archwires are able to deliver a consistent force after 30 days of deflection. However, the clinical applicability of these fibre-reinforced composite archwires may be limited as they are unable to sustain deflections of 2mm without experiencing crazing and loss of force delivery.

Limitations: Clinical efficacy of the aesthetic, fibre-reinforced composite orthodontic archwires remains to be observed.

Topic: [bone wires](#), [esthetics](#), [polymers](#), [titanium](#), [nickel](#), [t-test for a single group \(paired t-test\)](#)

Introduction

An orthodontist's treatment goals often are to achieve a functional, aesthetic, and stable dental occlusion and simultaneously maintain or improve facial harmony and balance. However, patients are typically most concerned with aesthetics, both during and after treatment. Currently, the most commonly used orthodontic appliances mainly consist of metal alloy brackets and archwires that are considered by many potential patients to be unaesthetic and undesirable. In recent years, there has been an increasing focus on dental aesthetics and the need for orthodontic treatment, which has led to an increase in adults seeking orthodontic treatment.¹ As the number of adults seeking orthodontic treatment has increased, so has the demand for a more aesthetic orthodontic appliance.² The use of an

aesthetic orthodontic archwire in concert with an aesthetic bracket, which is not yet common place in orthodontics, is likely the next step to enhance the aesthetics of orthodontic appliances.

There have been many advances in the physical properties of the current alloy archwires; however, they have mostly remained unaesthetic. Alloy archwires coated with a tooth coloured polymer have been developed for use during the initial treatment period but such coatings are not durable clinically.³ Efforts have been made to research and develop fibre-reinforced composite archwires suitable for use in clinical orthodontics,⁴⁻¹⁰ but commercial availability has been slow to progress. One fibre-reinforced composite archwire that is available commercially is from BioMers Products, LLC (Jacksonville, Florida, USA) whereby glass fibres in a polymer resin matrix are formed into archwires via a plastic, shrinkable die. Several reports have described these wires and/or their properties either in developmental stages¹¹⁻¹² or once marketed.¹³

Although aesthetics are desired by patients and orthodontists alike, proper and efficient function of the appliance is mandatory.¹⁴ When an archwire is deflected, the amount of force delivery should remain constant. However, polymer-based materials typically exhibit viscoelastic or time-dependent stress-strain behaviour, which may lead to decreased force delivery over time when used as an archwire.¹⁵ This decrease in force delivery, known as stress relaxation, is due to relaxation of the molecular conformations towards equilibrium, despite the constant deflection.¹⁶ Clinically, a decrease in force delivery over time would lead to inefficient tooth movement if the force levels decrease below the minimum threshold for tooth movement.⁹ The objective of this research was to determine if aesthetic, fibre-reinforced composite archwires can maintain continuous light forces without undergoing force decay. This study compared the amount of quasi force decay exhibited by commercially available fibre-reinforced composite archwires from BioMers Products, LLC to that of conventional nickel-titanium (NiTi) archwires.

Materials and methods

Round 0.018" fibre-reinforced composite archwires (Align A; BioMers Products, LLC) and 0.016" martensitic-stabilized NiTi (Nitinol

Classic, 3M Unitek, Monrovia, California, USA) archwires were used in this study. Larger dimensions of fibre-reinforced composite archwires are available from the manufacturer; however, previous research has shown that the smallest wire (Align A) is more flexible and less likely to experience crazing during three-point bending tests.¹⁷ Additionally, the smaller 0.016" martensitic-stabilized NiTi wires were used because it has bending values closer to Align A compared with 0.018" martensitic-stabilized NiTi.^{13,17}

This study examined the quasi force decay (or stress relaxation) properties of the above-mentioned wires. Force decay was determined utilizing a three-point bend test to measure the amount of force necessary to deflect a specimen. Fifteen archwires of each brand were used. For each archwire, two 25mm segments were sectioned from the distal ends of each archwire and allocated to one of two groups (1 or 2mm groups; $n = 15/\text{group}$). Each segment was tracked during all procedures. Segments were projected onto a screen along with a two-dimensional Cartesian grid comprised of 0.05×0.05 inch squares to measure the curvature of the segments. This was performed to determine the amount of curvature and/or deformation, if any, before initial testing, after the first three-point bend test, and after deflection for 30 days (mentioned below) to assure consistent bending configurations during testing. Curvature, the inverse of radius, was measured by fitting a circle of the same arc length as the segments to the grid. Due to the impracticality of measuring force decay of a single archwire for 30 days, the following protocol was used: each segment was tested in three-point bending (14mm distance between bottom supports with the load applied vertically in the middle of the specimen with a 2.0mm/min crosshead speed; 37°C in air) using a universal testing machine (Model 5500R; Instron Corp., Norwood, Massachusetts, USA) to a maximum deflection of 3.1mm and then it was returned to its starting position at the same rate;¹⁸ next, each segment was placed in a custom-made jig designed to deflect each segment either 1 or 2mm for 30 days in air at 37°C. This jig similarly had a 14mm span length and test supports of the same diameter (3.18mm) as used in the three-point bending testing. A 14mm span length was selected to be consistent with other bending studies that evaluated the fibre-reinforced composite archwires.^{13,17} Upon removal from the jig at 30 days, each segment was once again tested in three-point bending to examine consistency of the bending profile. Thus, it

should be noted that what was measured was not force decay in a traditional sense of measuring force values continuously over time, but with this protocol, the bending profile and force delivery characteristics were compared initially and after 30 days of continuous deflection. Consequently, for the purpose of this paper, the term quasi force decay has been used.

The slopes (g/mm) of the linear portions (from 0 deflection to approximately 0.75mm deflection) of the activation/deactivation curves and force (g) values at 1.0, 2.0, and 3.0mm during both activation and deactivation comprise the data examined from each test. Specifically, the slopes were taken between the 0.25 and 0.5mm deflection values during the respective activation/deactivation segments. Activation/deactivation modulus was then calculated from the activation/deactivation slopes according to the formula: $E = \text{Slope} * L^3 / (48 * I)$, where the slope is converted to N/mm, L is the span length (14mm), and I is the moment of inertia for a round wire. The Shapiro–Wilk test was performed on each variable in order to assess normality. If the variable was determined to be normally distributed at both test times (pre- and post-deflection), the paired t -test was performed. If the variable was found to be not normally distributed at either test time point, the non-parametric signed rank test was used. Since performing multiple t -tests increases the risk of a Type I error, the significance level was adjusted to 0.01 (SAS Institute Inc., Cary, North Carolina, USA). Additionally, a control group consisting of wires not subject to the 30-day constant deflection was also tested to ensure that the initial three-point bend test did not alter the material and impact the results from the second three-point bend test after 30 days.

Results

The curvatures of the fibre-reinforced composite and NiTi wire segments used in this testing were determined to be 0.01mm^{-1} or less, which was the approximate lower sensitivity limit using the two-dimensional Cartesian grid described above. Nevertheless, the segments did not increase in curvature after the initial three-point bending or after 30 days of deflection.

The observed bending profiles of fibre-reinforced composite archwires show similar force–deflection curves as those of NiTi archwires, only with slightly lower forces observed in the fibre-reinforced composite groups (Figure 1a). The force–deflection curves obtained for each of the NiTi test groups exhibited similar activation and deactivation curves for the pre-deflection and post-deflection bending profiles (Figure 1b–1d). Activation and deactivation force values may be found in Tables 1 and 2, respectively. Statistically significant ($P < 0.01$) differences in the pre-deflection and post-deflection stiffness and force values, during activation and deactivation, were evident in each of the NiTi test groups. Overall, however, the activation and deactivation force levels measured in the NiTi test groups were very consistent with small standard deviations (SDs).

Table 1. Bending values during activation

Archwire	Activation					# with crazing (after bend test for pre-deflection groups, after deflection for post- deflection groups)
	Stiffness (g/mm)	Modulus (GPa)	Force at 1mm (g)	Force at 2mm (g)	Force at 3mm (g)	
NiTi control: pre-deflection	126±2	56.0±0.9	123±1	224±2	270±6	0
NiTi control: post-deflection	121±2*	54.1±1.0*	120±3*	215±3*	257±4*	0
NiTi 1mm group: pre-deflection	126±2	56.0±0.8	123±2	223±3	267±3	0
NiTi 1mm group: post-deflection	120±2*	53.7±0.8*	119±1*	216±3*	262±6*	0
NiTi 2mm group: pre-deflection	126±1	56.1±0.6	124±1	224±2	268±4	0
NiTi 2mm group: post-deflection	120±1*	53.3±0.6*	118±1*	213±2*	256±5*	0
BioMers control: pre-deflection	101±9	27.2±2.4	99±10	182±17	220±19	1
BioMers control: post-deflection	99±9	26.6±2.3	96±8*	177±13*	217±15	1
BioMers 1mm group: pre-deflection	97±19	26.2±5.1	94±18	176±35	205±52	2

Archwire	Activation					# with crazing (after bend test for pre-deflection groups, after deflection for post- deflection groups)
	Stiffness (g/mm)	Modulus (GPa)	Force at 1mm (g)	Force at 2mm (g)	Force at 3mm (g)	
BioMers 1mm group: post- deflection	88±23*	23.5±6.3*	86±23*	158±42*	194±49*	2
BioMers 2mm group: pre- deflection	100±15	26.8±4.1	98±15	177±28	217±32	2
BioMers 2mm group: post- deflection	48±39*	12.9±10.5*	47±38*	86±69*	106±83*	12

NiTi, nickel-titanium. Within each parameter, * denotes a significant difference ($P < 0.01$) exists between pre- and post-deflection wires. $n = 15$ /archwire group.

Table 2. Bending values during deactivation

Archwire	Deactivation					
	Stiffness (g/mm)	Modulus (GPa)	Force at 3mm (g)	Force at 2mm (g)	Force at 1mm (g)	Elastic recovery (%)
NiTi control: pre- deflection	118±1	52.8±0.6	248±3	179±3	112±1	99.1±0.6
NiTi control: post- deflection	114±2*	50.7±0.8*	239±2*	177±2	109±2*	99.4±0.4
NiTi 1mm group: pre- deflection	118±2	52.6±1.0	249±9	181±4	114±8	99.5±0.5
NiTi 1mm group: post- deflection	113±2*	50.5±0.7*	241±3*	175±2*	108±2*	99.3±0.6
NiTi 2mm group: pre- deflection	120±2	53.3±0.8	248±3	180±2	113±1	99.2±0.4
NiTi 2mm group: post- deflection	112±1*	50.0±0.5*	238±3*	174±2*	106±2*	98.8±0.6
BioMers control: pre- deflection	90±6	24.1±1.7	201±13	157±10	86±6	99.0 ± 0.07
BioMers control: post- deflection	89±7	23.9±1.9	200±13	156±11	85±7	99.1±0.7
BioMers 1mm group: pre- deflection	80±24	21.6±6.6	187±49	140±40	76±23	98.5±1.4

Archwire	Deactivation					
	Stiffness (g/mm)	Modulus (GPa)	Force at 3mm (g)	Force at 2mm (g)	Force at 1mm (g)	Elastic recovery (%)
BioMers 1mm group: post-deflection	77±21	20.8±5.7	178±45*	136±37	74±21	98.8±1.1
BioMers 2mm group: pre-deflection	83±25	22.2±6.6	196±36	144±41	79±24	98.6±2.3
BioMers 2mm group: post-deflection	37±38*	10.1±10.1*	94±79*	66±66*	36±37*	99.1±1.9

NiTi, nickel-titanium. Within each parameter, * denotes a significant difference ($P < 0.01$) exists between pre- and post-deflection wires. $n = 15$ /archwire group.

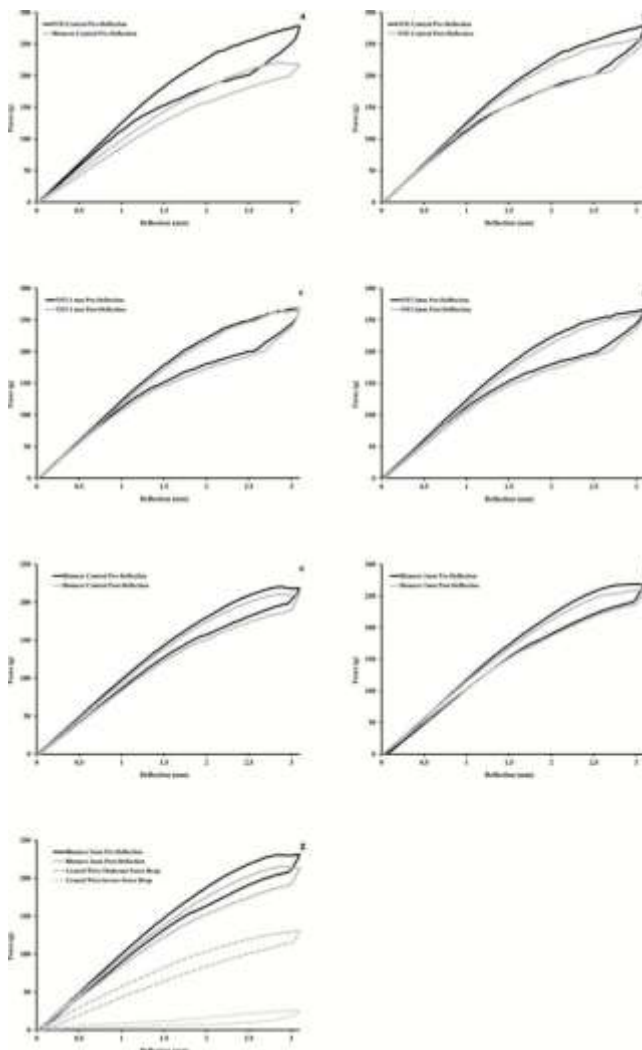


Figure 1. Comparison of typical force–deflection curves of (a) nickel–titanium (NiTi) archwires and fibre-reinforced composite archwires, (b) the NiTi control group, (c) the

NiTi 1mm deflection group, (d) the NiTi 2mm deflection group, (e) the fibre-reinforced composite control group, (f) the fibre-reinforced composite 1mm deflection group, (g) the fibre-reinforced composite 2mm deflection group (note: the curves for the crazed specimens are from different paired archwires).

Similar activation and deactivation curves, for the pre-deflection and post-deflection bending profiles, were found in the BioMers control group as well as the BioMers 1mm deflection group (Figure 1e and 1f). The differences in the pre-deflection and post-deflection activation and deactivation values were not statistically significant ($P > 0.01$; Tables 1 and 2) for the majority of comparisons. For those that were statistically significant, the values of the stiffness and force values were within 97 per cent of each other in the control group and within 90 per cent in the BioMers 1mm deflection group. Statistically significant ($P < 0.01$) differences in all of the pre-deflection and post-deflection stiffness and force values, during activation and deactivation, were evident in the BioMers 2mm deflection group (Figure 1g). The BioMers 2mm deflection group failed to deliver consistent forces as 80 per cent of the wires experienced varying amounts of crazing during the 30-day deflection period (Figure 2). Thus, the post-deflection force levels measured in the BioMers 2mm group were highly variable and the mean value was approximately 46–48 per cent of the pre-deflection force levels. The activation and deactivation force levels for the few wires that did not experience crazing were close to pre-deflection values, whereas the crazed wires exhibited large decreases in activation and deactivation force levels.



Figure 2. Comparison of non-crazed (top) and crazed (bottom) fibre-reinforced composite archwire.

Discussion

The fibre-reinforced composite archwires possessed a similar bending profile but delivered lower force levels than the martensitic-stabilized NiTi archwires despite their larger dimension (Figure 1a). These findings are in harmony with a recent study that found while fibre-reinforced composite archwires are less stiff and deliver less force than NiTi archwires of the same dimension, they have bending properties similar to NiTi and force levels within the same range.¹³

NiTi archwires are time tested and have a record of great clinical efficacy due to their high springback, flexibility, and resistance to plastic deformation as well as the ability to maintain a continuous light force over a long range of time, regardless of the amount of deflection.¹⁹ For fibre-reinforced composite archwires to be considered as a viable treatment alternative for NiTi archwires, they must not experience large amounts of stress relaxation and they must be able to undergo large deflections without permanently deforming or crazing. The results from the BioMers 1mm deflection group showed that fibre-reinforced composite archwires are able to deliver consistent force levels following a long period of deflection (Figure 1f). However, the results from the BioMers 2mm deflection group demonstrate that fibre-reinforced composite archwires are unable to predictably resist crazing when being deflected 2mm over a long period of time, resulting in delivery of inconsistent force levels (Figure 1g). Of the 15 segments tested in the BioMers 2mm deflection group, 7 experienced severe crazing during the 30-day deflection period and exhibited extremely low force levels in the post-deflection three-point bending tests. Moderate force levels were observed in four of the crazed segments and force levels similar to pre-deflection values were measured in one crazed segment and the three segments that did not craze during testing. The large variation observed within the BioMers 2mm test group is the reason the SDs for this group are so high (Tables 1 and 2). The clinical applicability of these fibre-reinforced composite archwires may be limited since only 20 per cent of the wires in the BioMers 2mm deflection group were able to resist crazing/cracking during prolonged deflection and subsequently maintain their initial force levels.

It should be noted that the term crazing is used here to describe the structural change in the fibre-reinforced composite archwires because that term accurately describes the appearance of the wire (Figure 2), i.e. whitening of the wire, consistent with how crazing appears in polymer-based materials. Additionally, the manufacturer's literature describes the process as crazing when excessive forces cause the resin to crack. In the wires tested in this study, the exact failure mechanism was not explored. It may well be that the resin surrounding the reinforcing fibres cracking is the cause of the crazing appearance. Another possible explanation is that when fibre-reinforced composite archwires undergo long periods of deflection, the constant strain causes the interface of the fibres and polymer matrix to fail, which then transfers the load to the brittle fibres, resulting in fracture of the fibres. Further study using failure analysis via microscopy or other techniques appears warranted to investigate the cause of the crazing and associated drop in force values. In a similar fibre-reinforced composite wire, Scabell *et al.*²⁰ observed failure via debonding and sliding at the interface fibre/matrix, which resulted in fibre pull out and crack propagation longitudinally along the polymer matrix.

During the initial three-point bend test, each wire segment was deflected 3.1mm as in the American Dental Association (ADA) specification for orthodontic wires. While only 2 of the wire segments from the BioMers 2mm deflection group crazed due to the 3.1mm deflection, 12 wire segments experienced variable amounts of crazing while being stored at a deflection of 2mm. This suggests that there is a period of time in which fibre-reinforced composite archwires are able to successfully withstand deflections of 2mm or greater before they fail. As it was impractical to measure the force levels exerted by a deflected archwire for a period of 30 days, it is unclear when during the deflection period each of these wires crazed. If data were available regarding when each wire failed during the 30-day deflection period, it could provide insight as to how long a practitioner could leave these wires in place and expect them to provide reasonably effective force levels. Additionally, as force is transferred from the wire to the teeth, the resulting tooth movement will serve to decrease the deflection of the wire. Because of the time-dependent stress-strain behaviour exhibited by polymeric wires, it is possible to recover a portion of the deformation and the force loss once the deflection is decreased.¹⁶ It is

also possible that a reduction in the amount of deflection may result in fewer crazes/cracks and more consistent force delivery.

In this study, the statistically significant ($P < 0.01$) differences in each of the NiTi test groups were unexpected. As mentioned previously, the force levels in the NiTi test groups were very consistent, resulting in small SDs within each test group. Thus, the statistically significant difference may be attributed to the small SDs. Force levels necessary for tooth movement, which varies depending on the type of movement desired, are typically in the 50g range but can be as low as 10g.²¹ In the NiTi test groups, the average difference between pre-deflection and post-deflection stiffness (g/mm), for activation and deactivation, was less than 6g/mm resulting in average stiffness levels of approximately 120g at 1mm (Tables 1 and 2); thus, it is evident that though the measured force levels were reduced by a statistically significant amount, the decrease in force observed in the NiTi groups was not clinically significant.

A limitation of the present study is that the constant deflection of the wires was conducted in air (at 37°C), whereas clinically they will be exposed to the oral environment with dynamic exposure media including saliva and various beverages. The reasoning behind this choice was to limit variables so as to solely ascertain the effect of constant deflection of force delivery. Chang *et al.*¹⁷ observed some larger dimension fibre-reinforced composite wires to exhibit greater crazing and loss of force delivery after exposure to water for 30 days. It is likely that force decay and/or the extent of crazing would be greater when the combination of constant strain and water/fluid exposure are combined. Another consideration for the present study is that ADA Specification No. 32 was used as a guide for three-point testing, with the span length exception noted above. Other researchers have evaluated the bending properties of various archwires using ISO 15841 or other protocols that differ slightly from that used in the present study, so comparison to other results is limited. Ultimately, however, the performance of these wires will need to be investigated in appropriately designed clinical studies.

Conclusions

1. Fibre-reinforced composite archwires exhibit bending profiles similar to those of martensitic-stabilized NiTi archwires but deliver lower forces.
2. Following 30 days of a continuous 1mm deflection, fibre-reinforced composite archwires do not exhibit clinically significant amounts of force decay as they are able to deliver post-deflection force levels consistent with their pre-deflection force levels.
3. The clinical applicability of fibre-reinforced composite archwires may be limited as the majority of the tested wires were unable to sustain deflections of 2mm without crazing and experiencing a statistically and clinically significant decrease in force delivery.

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