

Photo-elastic stress analysis of initial alignment archwires

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SUMMARY Photo-elastic models replicating a lower arch with a moderate degree of lower incisor crowding and a palatally displaced maxillary canine were used to evaluate the stresses transmitted to the roots of the teeth by initial alignment archwires. Six initial alignment archwires were compared, two multi-strand stainless steel wires, two non-super-elastic (stabilized martensitic form) nickel titanium wires, and two stress-induced super-elastic (austenitic active) nickel titanium wires. Three specimens of each archwire type were tested.

Analysis of the photo-elastic fringe patterns, in the medium supporting the teeth, revealed that the non-super-elastic nickel titanium archwires produced the highest shear stresses ($P = 0.001$). However, the shear stresses generated by the super-elastic alignment archwires and the multi-strand stainless steel archwires were very similar ($P = 1.00$). These results show that even in situations where large deflections of initial alignment archwires are required, super-elastic archwires do not appear to have any marked advantage over multi-strand stainless steel alignment archwires in terms of the stresses transferred to the roots of the teeth.

Introduction

Initial alignment is the first stage of orthodontic treatment and involves levelling, and correction of rotational and labiolingual displacements. Light tipping forces are recommended during this stage as the crowns of the teeth are often more displaced than the root apices (Proffit, 1993). At present the orthodontist can choose from a wide variety of multi-strand stainless steel or nickel titanium archwires when selecting an initial alignment archwire. However, when deciding on the relative merits of individual alignment archwires the clinician often has difficulty in extrapolating laboratory tests to the clinical situation. Further confusion is caused by the failure of clinical studies to fully support the clinical advantages claimed by the manufacturers. Different *in vitro* methods have been used to evaluate the mechanical properties of initial alignment archwires: the three-point bending test (Kusy and Stevens, 1987; Nakano *et al.*, 1999), the three-bracket method (Segner and Ibe, 1995), and the use of simulated arch forms (Hudgins *et al.*, 1990). However, no agreement exists on the most appropriate *in vitro* method of evaluating the mechanical properties of orthodontic archwires (Lopez *et al.*, 1979; Nikolai *et al.*, 1988; Rock and Wilson, 1988; Oltjen *et al.*, 1997). There are real concerns that laboratory tests are failing to reproduce the complex mechanical interaction that exists between archwires and brackets in the fully bonded arch (Evans *et al.*, 1998). Four randomized prospective clinical trials have evaluated the aligning and levelling properties of the various alignment archwires (O'Brien *et al.*, 1990; West *et al.*, 1995; Cobb *et al.*, 1998; Evans *et al.*, 1998). These

clinical studies have failed to demonstrate any significant differences in the aligning capabilities of super-elastic nickel titanium archwires when compared with Nitinol or multi-strand stainless steel archwires. It has been speculated that in routine clinical practice nickel titanium wires might not be deflected sufficiently to take advantage of their mechanical properties or that individual patient variations in metabolic response might negate the mechanical advantages of nickel titanium wires (Evans *et al.*, 1998). Since clinical studies have shown that multi-strand stainless steel and nickel titanium alignment archwires are equally effective, the case for using the more expensive nickel titanium archwires appears to rest on the claim that nickel titanium archwires exert lighter forces (Nakano *et al.*, 1999). When lighter forces are transmitted to the roots of the teeth there is less patient discomfort and root resorption (Reitan and Rygh, 1994). In the present study, a dynamic photo-elastic model was used to evaluate the stresses transmitted to the roots of the teeth by initial alignment archwires. Two common clinical scenarios were studied: lower incisor crowding and palatal canine ectopia.

Materials and methods

The photo-elastic material

The development of the gelatine photo-elastic orthodontic model has been reported previously (Clifford *et al.*, 1999). Photo-elastic analysis is an optical technique that is widely employed for examining and measuring stress distributions in structures subjected to internal or external forces. Polarized light is transmitted through

a photo-elastic active material that is doubly refractive when stressed. When the emergent light waves are viewed through an analyser filter the stress patterns appear as fringes or bands of colour. Gelatine is an extremely sensitive photo-elastic material, which exhibits a high level of mechanical creep (Richards and Mark, 1966). This property of mechanical creep (time-dependent deformation under loading) has been shown to allow teeth embedded in gelatine to respond to orthodontic forces in a manner similar to that encountered clinically (Clifford *et al.*, 1999). However, one of the disadvantages of gelatine is its susceptibility to tearing (Clifford *et al.*, 1999). Prior to this study, experiments were completed to overcome this problem and produce a more durable gelatine mixture (Badran, 2000). Ten grams of gelatine (Sigma-Aldrich Company Limited, Dorset, UK) having a Bloom value of 300 (a measure of the strength of gelatine) mixed with 5 ml of glycerine and 100 ml of water was found to produce a mixture that has maximum resistance to tearing under tensile stress. This mixture also showed high levels of mechanical creep and high optical sensitivity.

The lower incisor crowding experimental model

A full mandibular arch (from left to right second molars) was constructed using previously extracted human teeth. Contralateral teeth were selected to match as closely as possible shape, crown size, and root length. Black pin markers were placed in the centres of the crowns and on the root tips of the incisors and premolars. Two pins were placed on the crowns of the molar teeth, in the mesial and the distal triangular fossae, and on all the root tips. Pre-adjusted edgewise brackets and molar tubes (0.022-inch slot, Andrews prescription, Forestadent, Milton Keynes, UK) were bonded to the crowns of the teeth. The roots of the teeth were embedded in silicone-rubber impression material (Blend-a-gum, Crest Research, Forskning, Germany) to reproduce a complete lower arch using a pre-formed 0.019 × 0.025-inch stainless steel archwire ligated to the brackets. The transverse dimensions of this archwire matched exactly the transverse dimensions of the alignment archwires tested later in the study. The anterior segment of the impression containing the incisors was cut free from the main impression and 8 mm of incisor crowding was introduced. The crowns of the teeth were then embedded in silicone-rubber impression material held within a vacuum-formed plastic template. The impression material was removed from around the roots of the teeth, which were then embedded in the gelatine solution contained in an arch-shaped glass mould. Twenty-four hours later when the gelatine was set the plastic template and the impression of the crowns were removed. This template and master impression were retained and used to place the teeth in the same position at the beginning of each subsequent experiment.

The ectopic maxillary canine experimental model

Prior to constructing this photo-elastic model the average displacement of palatally ectopic maxillary canines was determined. Pre-treatment study casts of 20 patients who had open surgical exposure for palatal canine ectopia were recovered from the departmental model store. In all cases, the study casts were taken six months after surgical exposure when the ectopic canine was fully erupted in the palate. The mean distance from the line of the arch to the tip of the cusp of the displaced canine was 6 mm. The maxillary photo-elastic model was constructed in the same way as the mandibular photo-elastic model, but in the maxillary model the teeth were well aligned except for the upper right canine, which was positioned 6 mm palatal to the line of the arch.

A fresh gelatine mix was used for each experiment with initial tooth positions standardized using the master impressions and vacuum-formed template. Three fixed spheres (5 mm diameter) were attached to the outer surface of the glass mould adjacent to the second molars and one adjacent to the central incisors to act as reference points. All experiments were completed within a temperature-controlled environment at 22°C, free from external radiation sources, convective air currents, and extremes of humidity. At the start of each experiment fringes in a small sample of the gelatine were observed using diametrical compression to ensure that the photo-elastic properties of each gelatine mix were identical.

The archwires tested

Six initial alignment archwires were compared in this study, two multi-strand stainless steel, two non-super-elastic (stabilized martensitic form) nickel titanium wires, and two stress-induced super-elastic (austenitic active) nickel titanium wires (Table 1). The nickel titanium archwires were all preformed by the manufacturers to the same arch shape. The multi-strand stainless steel archwires were adjusted to match this shape prior to testing. All archwires were ligated with elastomeric modules using a ligature gun (Straight Shooter, TP Orthodontics Inc., Indiana, USA). This was done to ensure that the elastomeric modules were stretched in a uniform manner. Each of the six archwires was tested three times using a new archwire and a new gelatine mixture for each experiment. The force required to engage each archwire into the bracket on the palatally displaced maxillary right canine was measured using a strain gauge (Dentrix Tension Gauge, Ortho-Care, Bradford, UK).

Measurement of crown and root movements

Two manual SLR cameras, each with a standard 50-mm lens of the same focal depth, were placed on a camera mount, one above and one below the photo-elastic

Table 1 The initial alignment archwires tested.

Wire material	Size (inches)	Commercial name	Properties	Manufacturer
Stainless steel	0.015	Wildcat	3-strand	GAC, Orthocare
Stainless steel	0.0175	Wildcat	3-strand	Bradford
Nickel titanium	0.014	Nitinol Super-elastic	Active	3M Unitek
Nickel titanium	0.016	Nitinol Super-elastic	Austenitic	Monrovia, CA
Nickel titanium	0.014	Nitinol Classic	Stabilized	3M Unitek
Nickel titanium	0.016	Nitinol Classic	Martensitic	

orthodontic model. The test model was secured midway between the two cameras and photographic records were taken at eight different time intervals: before ligating the archwire, immediately after archwire ligation, and at 30 minutes, and 1, 2, 3, 8, and 24 hours after archwire ligation. Digitization of the photographs was performed using an SSI/Microcad Lightmaster (SSI Microcad, Wiltshire, UK) backlit digitizing system 1624LM-PC and a GTCO T5 16-button Clearvu cursor. The centres of the three reference points were digitized to define the x - y co-ordinate system and the positions of the black markers on the roots and crowns of the teeth were recorded. The magnification factor was calculated for each photograph and used to calculate the actual position of the teeth on the x - y co-ordinate system. A single operator (SB) digitized all photographs. To estimate digitization error one photograph was digitized 10 times, at one-week intervals. The standard deviations varied from 0 to 0.26 mm for both x and y co-ordinates, and the standard error was not greater than 0.08 mm for either co-ordinate direction. The reproducibility of the positions of the crowns and the roots of the teeth at the beginning of each experiment was tested using one-way analysis of variance (ANOVA). The standard deviations for the initial position of the crowns of the teeth on the x -axis were no greater than 0.62 mm and on the y -axis no greater than 0.51 mm ($P = 1.00$). The standard deviations for the initial positions of the roots of the teeth on the x and y axes were no greater than 0.68 and 0.56 mm, respectively ($P = 1.00$).

Photo-elastic stress analysis

A circular polariscope was used for the photo-elastic stress analysis. This basically comprises a light source emitting white light, a polarizer that transmits light in one plane and an analyser that receives the transmitted light and again only transmits in one plane. Photo-elastic fringes are of two types, isoclinic fringes that provide information about the directions of principal stresses, and isochromatic fringes, which give details about the magnitudes of the stresses. It is convenient to

regard isochromatic fringes as lines of uniform shear stress. Since the black isoclinic fringes may obscure the coloured isochromatic fringes, two quarter-wave plates were inserted to eliminate the isoclinic fringes. A Canon EOS 1000F camera focused manually (aperture value 5.6, shutter speed 1/15 second) with three close-up filters on an 85-mm lens was used to record the photo-elastic images on Fuji Super G plus 400 film (Fuji, Japan). The photographic method was standardized using the same object-to-lens distance and lighting conditions. Photographs of the stress patterns were taken at the same eight time intervals as the physical measurements. The isochromatic fringes (stress magnitude) were counted on each photograph using the method recommended by Kuske and Robertson (1974). Using this approach the magnitudes of the stresses (as identified by fringe order) are determined by noting the colour of the isochromatic fringes recorded. Zero order isochromatic fringes appear black on a coloured background and first order fringes are clearly identified as a distinct transition between the red and blue colours of the spectrum. Although this technique cannot resolve directly the principal tensile and compressive stress magnitudes in the three-dimensional gelatine field around the roots of the teeth, the isochromatic fringes allow comparison of the magnitude of stresses produced by different archwires. Using this technique, the stress indicated by a fringe order of two is double the magnitude of stress of a fringe order of one, etc. Repeatability was tested by the re-recording of 40 fringe order measurements one week after the original assessment. ANOVA showed that the repeatability was 0.4 of a fringe order, i.e. in only one in 20 assessments would a difference of 0.4 of a fringe order be expected in repeat measurements.

Results

Crown and root movements

Experiment 1: lower incisor crowding. The mean overall crown and root movements at the end of the 24-hour test period were similar for each archwire. No significant differences in the mean crown movements produced

by the different archwires were detected by ANOVA. However, a small, but statistically significant difference was found between the root movements produced by the 0.014-inch Nitinol Classic and the 0.016-inch Nitinol Super-elastic archwires (mean total root movement 0.63 mm and 0.29 mm, respectively, ANOVA, $P < 0.01$).

Experiment 2: ectopic maxillary canine. The mean forces required to engage each archwire in the bracket on the displaced canine are reported in Table 2. When archwires of a similar diameter were compared, the highest engagement forces were recorded for the Nitinol archwires followed by the super-elastic archwires and the multi-strand stainless steel archwires. The average crown and root movements at the end of the 24-hour test period are also reported in Table 2. When archwires of similar diameter were compared, the Nitinol archwires produced the greatest crown movement followed by the super-elastic archwires and then the multi-strand stainless steel archwires. For all the archwires, only very small movements of the root apex of the canine were observed (Table 2).

Arch width changes

Experiment 1: lower incisor crowding. The mean changes in inter-canine and inter-molar width for each of the archwires are shown in Table 3. No significant differences were detected between the archwires in their influence on

inter-canine and inter-molar width (ANOVA, $P > 0.05$). Each of the archwires produced a small increase in inter-canine distance and almost negligible changes in inter-molar distance.

Experiment 2: ectopic maxillary canine. In this experiment only inter-molar changes were registered. The transverse changes recorded at the end of the test period are also reported in Table 3. Only very small changes in inter-molar distance were observed with all the archwires.

Photo-elastic analysis

Experiment 1: lower incisor crowding. Inter-proximal fringe orders were measured to represent the magnitudes of shear stress between the teeth. Figure 1 shows the average fringe orders between the roots of the incisors for each of the six archwires. The highest mean shear stresses were recorded for the 0.014- and 0.016-inch Nitinol Classic (Table 4). The differences in the mean fringe orders for the entire arch over the 24-hour test period were analysed using the multiple comparisons test after adjusting the P -values by using the Bonferroni correction. This is the most conservative of the *post-hoc* tests and was carried out to ensure that spurious significant comparisons were not reported. Statistical analysis revealed that the shear stresses produced by the 0.016-inch Nitinol Classic archwires were significantly higher than all the other archwires with the exception of the

Table 2 Ectopic maxillary canine experiment: mean values (and range) for engagement force, crown movement, and root movement of the displaced canine for each archwire.

Archwire	Engagement force (g)	Crown movement (mm)	Root movement (mm)
0.015-inch Wildcat	62.5 (50–75)	4.72 (4.58–4.80)	1.01 (0.75–1.15)
0.0175-inch Wildcat	133.0 (125–150)	5.04 (4.85–5.18)	0.43 (0.31–0.65)
0.014-inch Nitinol Super-elastic	75.0 (75)	4.79 (4.48–5.16)	1.11 (1.0–1.18)
0.016-inch Nitinol Super-elastic	141.6 (125–150)	5.40 (5.27–5.50)	0.89 (0.78–0.99)
0.014-inch Nitinol Classic	87.5 (75–100)	4.88 (4.27–5.45)	0.95 (0.82–1.18)
0.016-inch Nitinol Classic	175.0 (175)	6.10 (6.02–6.15)	0.76 (0.68–0.82)

Table 3 The mean changes (and standard errors) in inter-canine and inter-molar distances produced by the alignment archwires in the lower incisor crowding experiment and the inter-molar changes recorded in the maxillary ectopic canine experiment.

Archwire	Lower incisor crowding experiment		Ectopic canine experiment
	Inter-canine change (mm)	Inter-molar change (mm)	Inter-molar change (mm)
0.015-inch Wildcat	0.15 (0.21)	–0.28 (0.08)	0.04 (0.12)
0.0175-inch Wildcat	0.88 (0.12)	0.00 (0.11)	0.11 (0.09)
0.014-inch Nitinol Super-elastic	0.35 (0.02)	–0.14 (0.08)	0.00 (0.12)
0.016-inch Nitinol Super-elastic	0.66 (0.29)	0.00 (0.12)	–0.19 (0.01)
0.014-inch Nitinol Classic	0.81 (0.13)	0.15 (0.07)	0.22 (0.05)
0.016-inch Nitinol Classic	0.82 (0.20)	0.07 (0.07)	–0.06 (0.06)

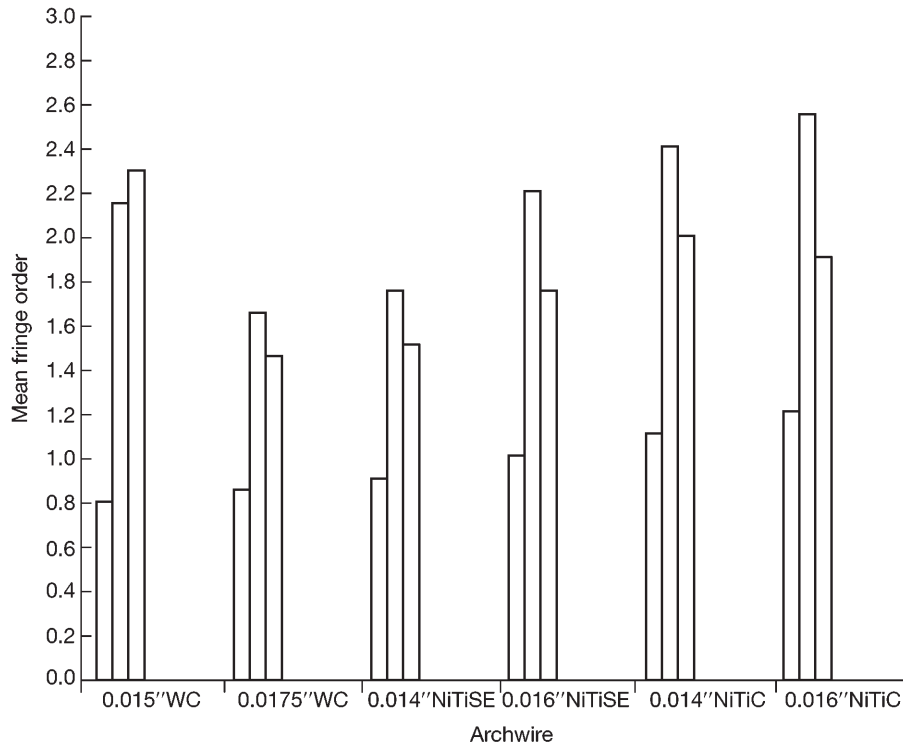


Figure 1 Experiment 1: lower incisor crowding. Mean fringe orders (shear stress) recorded between the incisors (2-1, 1-1, 1-2) for each of the alignment archwires.

Table 4 The mean fringe orders (and 95 per cent confidence intervals) recorded for each archwire.

Archwire	Lower incisor crowding experiment		Ectopic canine experiment
	Mean overall fringe order	Mean fringe order on initial engagement	Mean fringe order after 24 hours
0.015-inch Wildcat	1.13 (0.06)	2.17 (0.15)	2.48 (0.10)
0.0175-inch Wildcat	0.97 (0.06)	2.45 (0.15)	2.68 (0.10)
0.014-inch Nitinol Super-elastic	0.98 (0.06)	2.31 (0.15)	2.55 (0.10)
0.016-inch Nitinol Super-elastic	1.13 (0.06)	2.43 (0.15)	2.63 (0.10)
0.014-inch Nitinol Classic	1.21 (0.06)	2.34 (0.15)	2.58 (0.10)
0.016-inch Nitinol Classic	1.32 (0.06)	2.70 (0.15)	2.71 (0.10)

0.014-inch Nitinol Classic (0.016-inch Nitinol Super-elastic, $P < 0.001$; 0.014-inch Nitinol Super-elastic, $P < 0.001$; 0.0175-inch Wildcat, $P < 0.001$; 0.015-inch Wildcat, $P = 0.001$). The 0.014-inch Nitinol Classic produced significantly larger shear stresses than the 0.014-inch Nitinol Super-elastic ($P < 0.001$) and the 0.0175-inch Wildcat ($P < 0.001$).

The fringe orders recorded for the 0.014-inch Nitinol Super-elastic and the 0.0175-inch Wildcat archwires were significantly lower than all other archwires (Table 4). For all archwires the fringe orders remained relatively constant over the test period.

Figure 2 shows examples of the fringe orders (stress patterns) recorded at 24 hours for 0.015-inch Wildcat,

the 0.016-inch Nitinol Super-elastic, and 0.016-inch Nitinol Classic archwires.

Experiment 2: ectopic maxillary canine. The mean fringe orders around the root of the displaced canine when the archwires were initially engaged and at 24 hours are reported in Table 4. Figure 3 shows the average fringe orders around the root of the displaced canine for each of the six archwires. On initial engagement of the archwires the shear stresses produced by the 0.016-inch Nitinol Classic archwires were significantly higher than those produced by the 0.015-inch Wildcat ($P = 0.001$) and the 0.014-inch Nitinol super-elastic archwires ($P = 0.03$). However, after 24 hours no significant differences existed

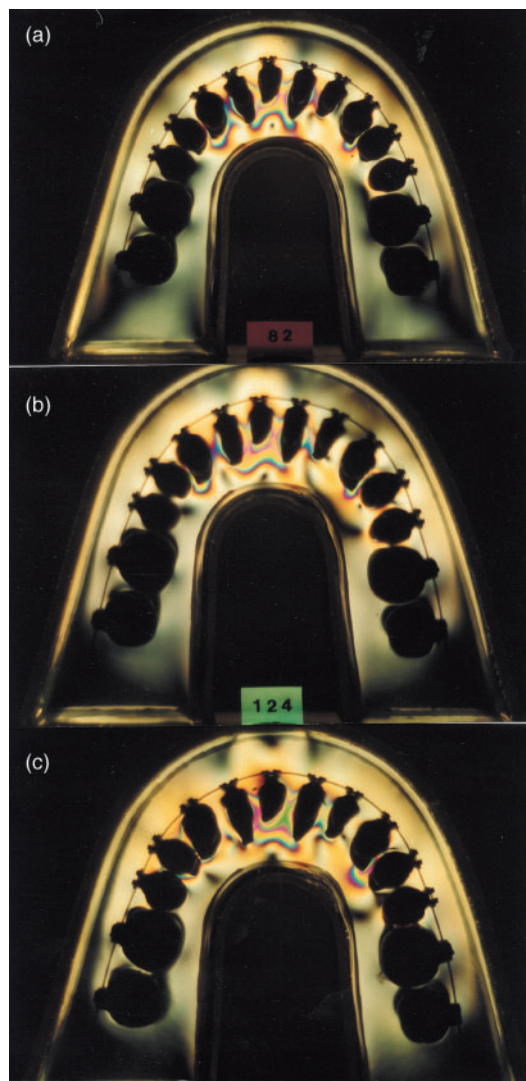


Figure 2 Experiment 1: lower incisor crowding. Photo-elastic stress patterns recorded at 24 hours for (a) 0.015-inch Wildcat; (b) 0.016-inch Nitinol Super-elastic; (c) 0.016-inch Nitinol Classic.

between any of the archwires in terms of the fringe orders and, hence, shear stresses recorded.

Figure 4 shows examples of the fringe orders (stress patterns) recorded at initial engagement and at 24 hours for the 0.015-inch Wildcat, 0.016-inch Nitinol Super-elastic, and 0.016-inch Nitinol Classic archwires. These demonstrate the greater shear stresses produced by the 0.016-inch Nitinol archwire (Figure 4e) when initially engaged. They also show the fringe patterns to be mostly concentrated around the roots of the canine and adjacent first premolar and lateral incisor.

Discussion

This study set out to determine whether any clinically important advantage can be gained from using a

particular type of alignment archwire. Despite the manufacturers' claims of superiority, all previous clinical investigations have failed to identify any significant difference among the various initial alignment archwires (O'Brien *et al.*, 1990; West *et al.*, 1995; Cobb *et al.*, 1998; Evans *et al.*, 1998). Nickel titanium archwires typically cost four to six times more than multi-strand stainless steel archwires (Rubin, 1999). There are therefore good economic reasons for attempting to clearly establish the exact clinical advantages of nickel titanium archwires over multi-strand stainless steel.

In this investigation, a gelatine mixture with excellent photo-elastic properties was used to represent alveolar bone. The gelatine mixture also exhibited a high creep rate (time-dependent deformation under loading), which permitted the teeth to move to new positions without elastic recovery. The photo-elastic properties of the gelatine mixture allowed the longitudinal analysis of changes in stress distribution around the roots of the teeth. Previous studies using the gelatine photo-elastic orthodontic model have found that the type and magnitude of tooth movements recorded in response to orthodontic forces are similar to those noted clinically (Clifford *et al.*, 1999). It is not known whether this model exactly replicates the complex clinical situation where teeth attached to alveolar bone by a periodontal ligament are surrounded by soft tissues and subjected to occlusal forces. However, the model may provide a more realistic representation of the clinical situation than any other laboratory tests to date. A major advantage is the ability to evaluate the performance of an archwire when ligated to an entire arch of teeth using real brackets and ligatures, thereby reproducing the effects of inter-bracket span and friction.

When using this type of experimental model it is important that any variations detected can be attributed to the mechanical properties of the archwires, rather than differences in the initial positions of the teeth or variations in arch dimensions. The evaluation of the reproducibility of the experimental model revealed that at the beginning of each of the tests the arch dimensions and the positions of the crowns and roots were replicated with a high degree of accuracy.

The nickel titanium archwires used in orthodontic practice are of two types: work-hardened and super-elastic. The super-elastic archwires used in this study were austenitic active alloys that undergo phase transformation (to the martensitic form) on application of stress, whereas Nitinol has a stabilized martensitic structure, where the shape memory effect (super-elastic behaviour) has been suppressed by cold-working. The term super-elastic implies that an archwire exerts the same force independently of deflection (Burstone *et al.*, 1985). Bending a super-elastic wire in its austenitic phase creates a stress-induced martensitic transformation that is reversed when strain is reduced. Super-elastic behaviour only occurs at

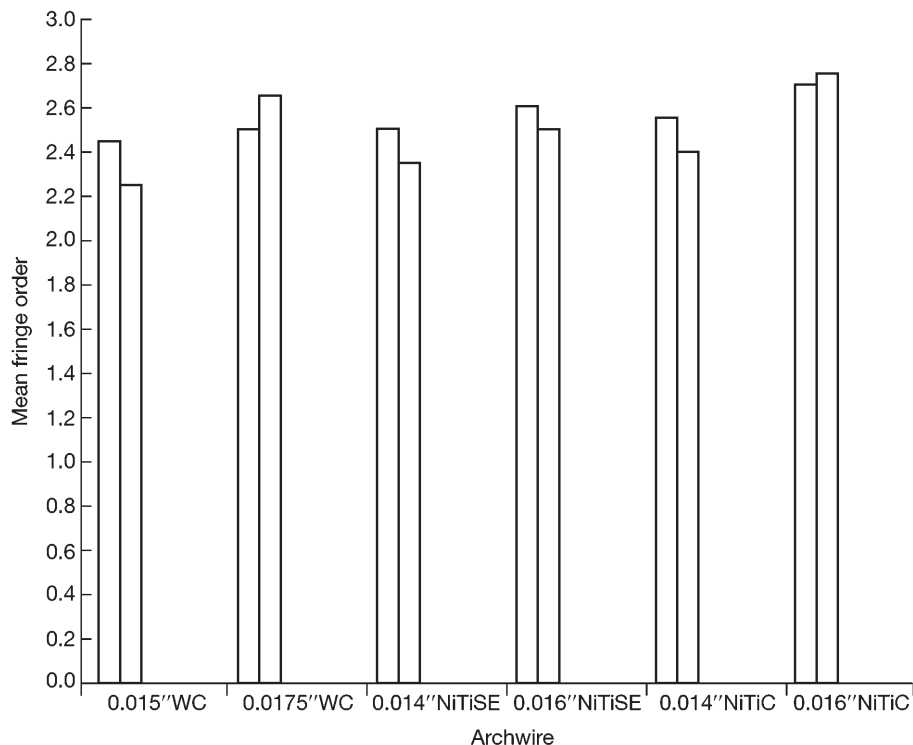


Figure 3 Experiment 2: ectopic maxillary canine. Mean fringe orders (shear stress) recorded around the displaced canine (4-3, 3-2) for each of the alignment archwires when initially engaged.

temperatures within the transition temperature range (Andreasen *et al.*, 1985). A previous study of a range of super-elastic NiTi springs reported that all the springs tested showed super-elastic properties at room temperature and super-elastic properties were only lost when the temperature fell below 12.7°C (Barwart *et al.*, 1999). In the present study the temperature was maintained well above this level (22°C).

In the first experiment, a lower arch was constructed with 8 mm of lower incisor crowding to represent the average clinical situation. Little *et al.* (1981) reported that the average amount of pre-treatment lower incisor crowding present in the series of Class I malocclusions that they studied was 8.14 mm. In agreement with previous clinical investigations, each of the alignment archwires evaluated in this study showed a similar ability to align the crowded incisor teeth. All the alignment archwires showed a tendency to increase the inter-canine distance slightly, even though the transverse dimensions of the experimental dental arch were the same as the archwires at the beginning of each experiment. The deflection of the anterior part of the alignment archwires as they engaged the crowded incisors might have produced this tendency for inter-canine expansion. This finding reinforces the importance of restoring the patient's arch form by careful adjustment of the stainless steel working archwires used after the initial alignment

archwires. No significant differences were found between the super-elastic archwires and the multi-strand stainless steel archwires in terms of the shear stresses recorded between the roots of the crowded incisor teeth. However, the Nitinol Classic archwires produced significantly higher shear stresses than both these types of archwire. These results in part confirm previous laboratory studies which found that super-elastic archwires produce lower forces than Nitinol archwires (Segner and Ibe, 1995; Nakano *et al.*, 1999).

The second experiment was designed to reproduce a realistic clinical scenario where the initial alignment archwire was deflected by an amount greater than that used when treating moderate lower incisor crowding. This was undertaken because some authors have speculated that super-elastic archwires may not express their super-elastic mechanical properties until they are deflected by at least 2 mm (Tonner and Waters, 1994). The 6 mm deflection used in this experiment can be considered to represent a large tooth displacement that can often be encountered in the clinical situation. The shear stresses recorded in this experiment were almost double those registered in the first photo-elastic experiment of moderate lower incisor crowding. When archwires of similar diameter were compared, the Nitinol Classic archwires had the highest initial engagement forces, produced the greatest shear stress, and resulted in the largest crown

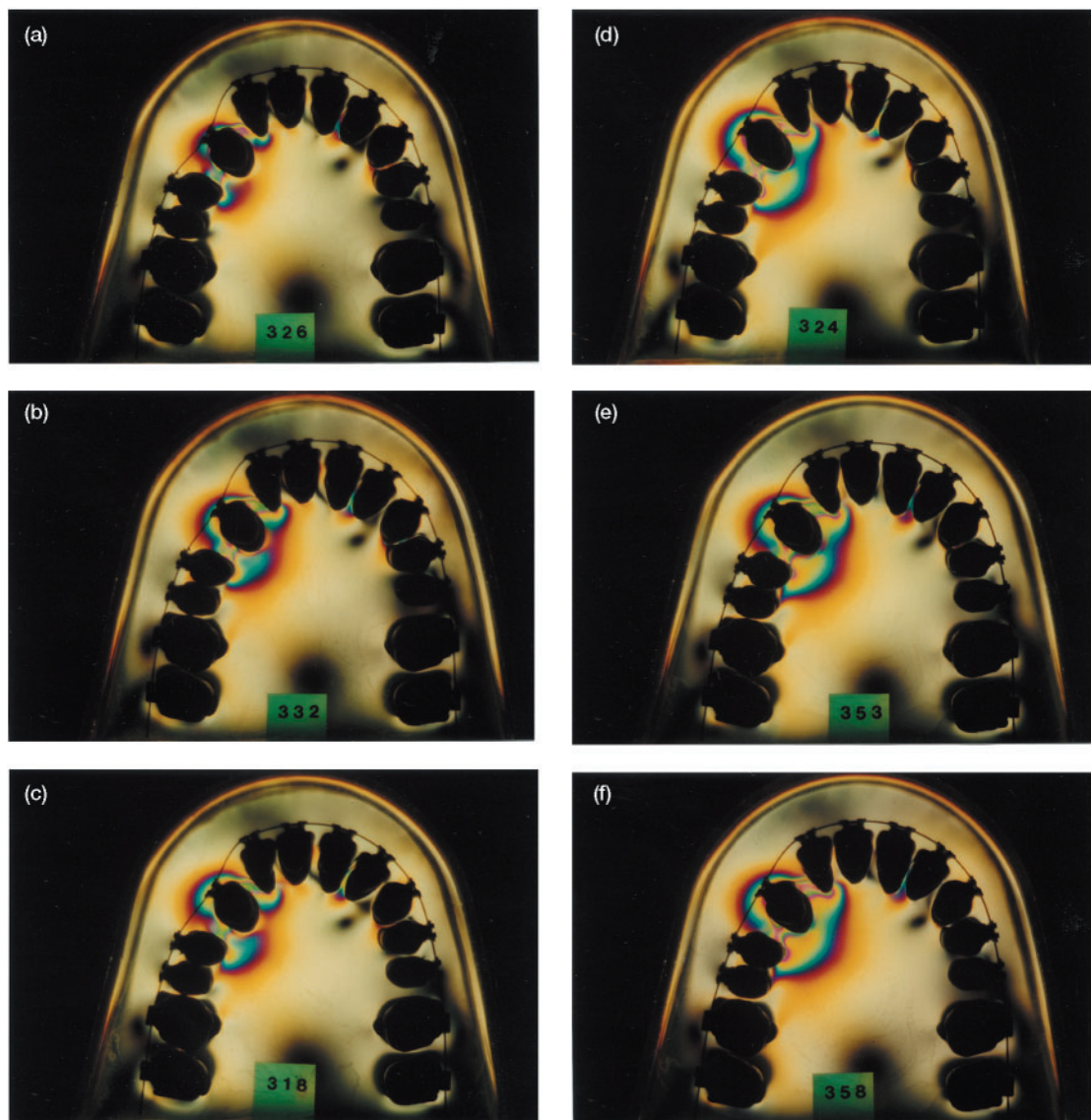


Figure 4 Experiment 2: ectopic maxillary canine. Photo-elastic stress patterns recorded for 0.015-inch Wildcat at (a) initial engagement and (b) 24 hours; 0.016-inch Nitinol Super-elastic at (c) initial engagement and (d) 24 hours; and 0.016-inch Nitinol Classic at (e) initial engagement and (f) 24 hours.

movements. However, despite the large deflection required to fully engage the archwires there was no evidence that the super-elastic archwires were superior to the multi-strand stainless steel archwires. Linge and Linge (1991) have speculated that orthodontic treatment mechanics might explain the higher prevalence of apical root resorption in lateral incisors adjacent to ectopic maxillary canines. Figure 4 provides evidence to support this hypothesis by revealing the distribution of shear stresses affecting the roots of the adjacent lateral incisor and first premolar, while the roots of the rest of the dentition remain relatively unaffected. It is also interesting to note that negligible changes in inter-molar distance occurred with all the archwires during alignment of the ectopic canine. Again, care should be taken

in extrapolating this finding to the clinical situation, but it is possible that the need for transverse anchorage support (using a transpalatal bar) when aligning palatally ectopic canines may have been overstated in the past.

No differences have been found in the pain reported by patients wearing super-elastic nickel titanium archwires or multi-strand stainless steel archwires (Jones and Chan, 1992). The present photo-elastic study supports the finding that the shear stresses produced by the multi-strand stainless steel archwires compare favourably with those created by super-elastic archwires. It could be that other factors such as the frictional conditions between the archwires, the elastomeric modules, and the brackets of the fully-bonded arch prevented the super-elastic archwires from demonstrating their full potential.

For nearly all the archwires, an increase in diameter was accompanied by an increase in mean shear stress. The photo-elastic experiments also found no evidence to support the view that multi-strand stainless steel archwires produce higher levels of stress in the initial phase of tooth movement.

Conclusions

The results of the photo-elastic experiments show that multi-strand stainless steel archwires and super-elastic nickel titanium archwires transfer similar stresses to the roots of the teeth. Both these types of archwires produced shear stresses 15–20 per cent lower than those recorded for Nitinol archwires of equivalent size. However, the differences in shear stress were small and it is debatable whether such small differences are clinically important, particularly for the smaller diameter archwires.

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References

- Andreasen G, Wass K, Chan K C 1985 A review of super-elastic and thermodynamic wire. *Quintessence International* 9: 623–626
- Badran S 2000 An investigation of orthodontic biomechanics using a dynamic photo-elastic model. PhD thesis, Queen's University, Belfast
- Barwart O, Rollinger J M, Burger A 1999 An evaluation of the transition temperature range of super-elastic orthodontic NiTi springs using differential scanning calorimetry. *European Journal of Orthodontics* 21: 497–502
- Burstone C J, Qin B, Morton J Y 1985 Chinese NiTi wire—a new orthodontic alloy. *American Journal of Orthodontics* 87: 445–452
- Clifford P M, Orr J F, Burden D J 1999 The effects of increasing the reverse curve of Spee in a lower archwire examined using a dynamic photo-elastic gelatine model. *European Journal of Orthodontics* 21: 213–222
- Cobb III N W, Kula K S, Phillips C, Proffit W R 1998 Efficiency of multi-strand steel, super-elastic Ni-Ti and ion-implanted Ni-Ti archwires for initial alignment. *Clinical Orthodontics and Research* 1: 12–19
- Evans T J W, Jones M L, Newcombe R G 1998 Clinical comparison and performance perspective of three aligning arch wires. *American Journal of Orthodontics and Dentofacial Orthopedics* 114: 32–39
- Hudgins J J, Bagby M D, Erickson L C 1990 The effect of long-term deflection on permanent deformation of nickel-titanium archwires. *Angle Orthodontist* 60: 283–288
- Jones M, Chan C 1992 The pain and discomfort experienced during orthodontic treatment: a randomized controlled clinical trial of two initial aligning arch wires. *American Journal of Orthodontics and Dentofacial Orthopedics* 102: 373–381
- Kuske A, Robertson G 1974 Photo-elastic stress analysis. John Wiley and Sons, New York
- Kusy R P, Stevens L E 1987 Triple-stranded stainless steel wires—evaluation of mechanical properties and comparison with titanium alloy alternatives. *Angle Orthodontist* 57: 18–32
- Linge L, Linge B O 1991 Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. *American Journal of Orthodontics and Dentofacial Orthopedics* 99: 35–43
- Little R M, Wallen T R, Riedel R A 1981 Stability and relapse of mandibular anterior alignment—first premolar extraction cases treated by traditional edgewise orthodontics. *American Journal of Orthodontics* 80: 349–365
- Lopez I, Goldberg J, Burstone C J 1979 Bending characteristics of Nitinol wire. *American Journal of Orthodontics* 75: 569–575
- Nakano H, Satoh K, Norris R, Jin T, Kamegai T, Ishikawa F, Katsura H 1999 Mechanical properties of several nickel-titanium alloy wires in three-point bending tests. *American Journal of Orthodontics and Dentofacial Orthopedics* 115: 390–395
- Nikolai R J, Anderson W T, Messersmith M L 1988 Structural responses of orthodontic wires in flexure from a proposed alternative to the existing specification test. *American Journal of Orthodontics and Dentofacial Orthopedics* 93: 496–504
- O'Brien K, Lewis D, Shaw W, Combe E 1990 A clinical trial of aligning archwires. *European Journal of Orthodontics* 12: 380–384
- Olthoff J M, Ducanson M G Jr, Ghosh J, Nanda R S, Currier G F 1997 Stiffness-deflection behavior of selected orthodontic wires. *Angle Orthodontist* 67: 209–218
- Proffit W R 1993 Contemporary orthodontics. Mosby, St Louis
- Reitan K, Rygh P 1994 Biomechanical principles and reactions. In: Graber T M, Vanarsdall R L (eds) *Orthodontics: current principles and techniques*. Mosby, St Louis
- Richards R, Mark R 1966 Gelatin models for photo-elastic analysis of gravity structures. *Experimental Mechanics* 6: 30–38
- Rock W P, Wilson H J 1988 Forces exerted by orthodontic aligning archwires. *British Journal of Orthodontics* 15: 255–259
- Rubin R 1999 Guest editorial—putting nickel titanium wire in its place. *Angle Orthodontist* 69: 214
- Segner D, Ibe D 1995 Properties of super-elastic wires and their relevance to orthodontic treatment. *European Journal of Orthodontics* 17: 395–402
- Tonner R I M, Waters N E 1994 The characteristics of super-elastic Ni-Ti wires in three-point bending. Part I: the effect of temperature. *European Journal of Orthodontics* 16: 409–419
- West A E, Jones M L, Newcombe R G 1995 Multiflex versus super-elastic: a randomized clinical trial of the tooth alignment ability of initial arch wires. *American Journal of Orthodontics and Dentofacial Orthopedics* 108: 464–471

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