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The effects of increasing the reverse curve of Spee in a lower archwire examined using a dynamic photo-elastic gelatine model

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SUMMARY This paper describes the development and testing of a dynamic *in vitro* photo-elastic model for evaluating the effects of orthodontic mechanics on an entire arch of teeth. A model of a mandibular arch was made and the teeth were embedded in a gelatine material with a high level of mechanical creep which permitted tooth movement in response to orthodontic forces. The excellent photo-elastic properties of this material also facilitated the analysis of the stress distribution around the roots of the teeth. The model of a mandibular arch was used to investigate the tooth movements and stress distributions produced by increasing the reverse curve of Spee in a 0.018×0.025-inch stainless steel archwire.

The results revealed that a 1-mm reverse curve of Spee increased the arch length by 1.6 mm, but increasing the reverse curve of Spee to 5 mm did not increase arch length further. Photo-elastic analysis showed an increased stress distribution around the roots of the incisors and molars as the reverse curve of Spee was increased in the archwire.

Introduction

Detailed analysis of the changes that occur when fixed orthodontic appliances are fitted to an entire arch of teeth has always been problematical for orthodontic researchers. Clinical investigations have usually relied on the use of static records, such as study casts or radiographs. However, both these methods have limitations that are compounded by differences between individual patients in their occlusal and skeletal morphology, as well as craniofacial growth. As a result, researchers have developed various *in vitro* models to study more precisely the effects of orthodontic mechanics. These include the use of laser holographic interferometry (Burstone and Pryputniewicz, 1980) or strain gauges on dried skulls (Hata *et al.*, 1987). In recent years, the finite element method has been used extensively to evaluate the stresses produced by the application of orthodontic forces (Tanne *et al.*, 1987, 1989; Andersen *et al.*, 1991; McGuinness *et al.*, 1991, 1992; Cobo *et al.*, 1993; Jost-Brinkmann *et al.*, 1993; Wilson *et al.*, 1994). The finite element technique is an entirely theoretical computer model, and concerns exist that the conditions that prevail in a dental arch are almost impossible to determine and represent in a computer simulation (Caputo and Standlee, 1987). Finite element modelling also places heavy demands on computer capacity so that most studies have been limited to single tooth investigations or groups of teeth rather than entire arches.

Photo-elastic analysis is a widely employed optical technique for examining and measuring stress distributions in structures subjected to internal or external forces. In this technique, polarized light is transmitted through a photo-elastic active material, which 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. Several comprehensive reviews have revealed that photo-elastic studies have found relevance in the biomechanical field since the 1930s (Orr, 1992; Zaida, 1993). In orthodontics, the photo-elastic technique has been used to examine the stresses induced during canine retraction (Caputo *et al.*, 1974; Baeten, 1975), with lingual appliances (Chaconas *et al.*, 1990), during incisor retraction (Chaconas *et al.*, 1993), and the stresses produced by orthopaedic forces (Chaconas *et al.*, 1976). However, all these previous studies have used teeth embedded in rigid materials which only permit limited elastic movement. In orthodontic experiments, it would be advantageous to use an artificial model which simulates as closely as possible the tooth movements that occur clinically. Gelatine, a non-rigid photo-elastic material, has been used for stress analysis in engineering studies (Richards and Mark, 1966) and the biological sciences (Full *et al.*, 1995). Gelatine is an extremely sensitive photo-elastic material, which exhibits a high level of mechanical creep (Richards and Mark, 1966). This unique property of mechanical creep (time-dependent deformation under loading) offered the opportunity to develop an *in vitro* model, which would permit orthodontic tooth movement. The research outlined in this paper reports the development of a dynamic photo-elastic model for studying orthodontic tooth mechanics. The model was used to evaluate the effects of increasing the reverse curve of Spee in a rectangular stainless steel archwire when reducing an increased overbite.

Materials and methods

Development of the dynamic photo-elastic orthodontic model

Initial experiments were carried out to discover the most suitable gelatine mixture for orthodontic experiments. Previous researchers had recommended various mixtures of gelatine, glycerine, and water (Kuske and Robertson, 1974; Full *et al.*, 1995). In the initial experiments, four concentrations of gelatine (6, 8, 10, and 12 g in 100 ml of water) were used to produce gelatine discs. The gelatine discs were subjected to a diametrical force in a specially constructed jig to evaluate their photo-elastic sensitivity and mechanical creep properties. It was found that 12 g of gelatine dissolved in 100 ml of water and mixed with 5 ml of glycerine produced a photo-elastically sensitive material, which exhibited sufficient mechanical creep to allow tooth movement. This gelatine mixture showed excellent adhesion to the roots of natural teeth, such that clearly visible tears occurred in the gelatine mixture if excessively large forces were applied to the teeth.

An experimental model of an entire lower arch with a 4-mm curve of Spee was constructed. Previously extracted human teeth were used to reproduce this lower arch from the lower right second molar to the lower left second molar. Contralateral teeth of similar dimensions were selected for this purpose. Pre-adjusted edgewise brackets with a 0.022-inch slot (Orthodontic Organiser, Manchester, England) were bonded to all the teeth in the normal manner. A curve was introduced into a preformed 0.018×0.025-inch stainless steel archwire to represent a 4-mm curve of Spee, midway between the anterior and posterior limits of the archwire, and all torque was removed from the archwire. The teeth were then ligated to this archwire and their roots embedded in wax. An impression was taken over the crowns of the teeth using a rubber-based impression material (Acumold, Wright Health Group Limited, Dundee, Scotland). This master impression was used to place the teeth in a similar initial position for each experiment. With the crowns of the teeth held in the master impression, the wax was removed from around the roots, which were then placed in a fresh mixture of gelatine held in a specially constructed arch-shaped glass container. A proprietary brand of pure granulated crystal gelatine (G. Costa & Company Limited, London) was used. The model was then refrigerated overnight in a commercial fridge between 0 and 5°C to ensure a more complete setting of the gelatine material.

Evaluation of the effects of increasing the reverse curve of Spee in a lower archwire

This experiment was designed to analyse the stress distribution and tooth movements produced by increasing the reverse curve of Spee in a lower 0.018×0.025-inch stainless steel archwire

(Orthocare, Bradford, England). A flat archwire and five different reverse curves of Spee (1, 2, 3, 4, and 5 mm) were tested in this study. The same archwire was used for each experiment. The reverse curve of Spee was placed in the archwire in such a way that the greatest depth of the curve was at the midpoint of the archwire. Prior to each test, the archwire was co-ordinated to match the transverse dimensions of the original archwire used to position the teeth in the master impression.

A fresh gelatine mix was used for each test with initial tooth positions standardized using the master impression described earlier. A calibration disc was made from a sample of the gelatine used in each of the experiments, and the photo-elastic and mechanical properties of each mix were assessed using a diametrical compression test. During each experiment the model was stored in an airtight container with a damp tissue lining the base of the container to minimize dehydration and only removed to carry out measurements. All experiments were undertaken at a constant room temperature of 18°C. To evaluate the possible influence of dehydration on the gelatine model, a control experiment was carried out with no archwire fitted. All experiments were conducted over a 9-hour period. Initial pilot work had revealed that all tooth movements were completed within this time period.

Physical measurements

A Baker Vernier travelling microscope (C. Baker, London, England) capable of measuring to the nearest 0.01 mm was used to record the changes in tooth position. Changes in arch length were calculated between amalgam markers on the occlusal surface of the second permanent molars and on the incisal edge of the central incisors. The antero-posterior movements of the incisors and the molars were determined in relation to fixed points on the glass container. The intercanine width, and intermolar widths between the first and second molars were also measured. Vertical changes in tooth position were recorded from a point on the orthodontic brackets to fixed points marked on the glass container. Incisor and molar tipping movements were registered using the molar bracket and amalgam markers placed on the buccal root surfaces.

All measurements were made on six occasions: before the introduction of the archwire, after ligating the archwire, and at 1, 2, 3, and 9 hours. To assess the influence of measurement error on the results an experimental model was constructed with the teeth embedded in dental plaster. This allowed duplicate measurements to be taken 1 week apart unaffected by dehydration.

Photo-elastic stress analysis

Photo-elastic fringes are of two types, isoclinic and isochromatic, giving information about stress directions and magnitudes, respectively. Both measurements are necessary to fully define a stress field. However, in this study the isochromatic fringes were used to define regions of high stress magnitude, and where little stress or material deformation was apparent. The aim was to identify modes of loading and, hence, changes of tooth orientation. 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 using Fuji Super G plus 400 film (Fuji, Japan) was used to record the photo-elastic images. The photographic method was standardized using the same object/lens distance and similar lighting conditions. A light source producing diffused white light and two polarizing filters (Sharples, Preston, England) were placed, one between the light source and model, and the other between the model and camera. No other light was allowed to enter the room. Photographs were taken at the same six intervals as the physical measurements: a lateral view showing the molars, second premolar, incisors, canine, and first premolar, and an anterior view of the incisors along the occlusal plane. Photographs were also taken from above the model to record any stress patterns lingual or buccal to the arch.

Results

The compression tests on the calibration discs taken from the individual gelatine mixes revealed that all the gelatine samples were equivalent

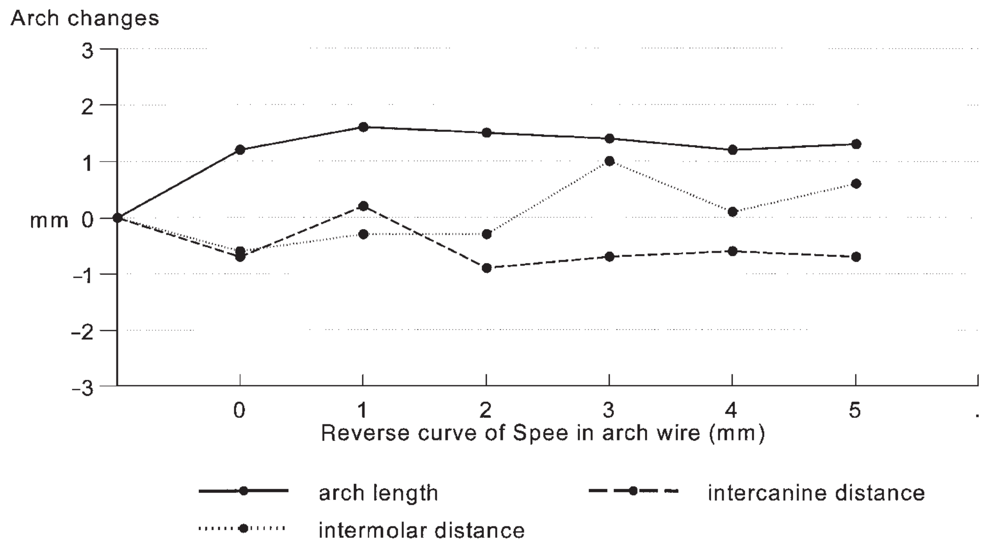


Figure 1 The changes in arch length, intercanine distance, and intermolar distance recorded for each reverse curve of Spee in the archwire.

in their mechanical and photo-elastic properties. The method error using the travelling microscope was found to be 0.2 mm for the 16 transverse, antero-posterior, and vertical measurements recorded. The control experiment, where no archwire was in place for a 9-hour period, revealed that there was very little tooth movement resulting from dehydration of the model. There was a small reduction in arch length (0.1 mm) and arch width (0.3 mm). Very small changes of 0.1 mm or less were also recorded in the vertical positions of the teeth. Photo-elastic analysis of the control model revealed no stress fringes.

The total changes in arch length, intercanine distance, and intermolar distance recorded for each archwire are illustrated in Figure 1.

Arch length

The results revealed that the arch length increased slightly during each of the experiments (Figure 1). The flat 0.018 × 0.025-inch stainless steel archwire produced an increase in arch length of 1.2 mm. When a 1-mm reverse curve of Spee was placed in the archwire, this produced a slightly larger increase in arch length (1.6 mm). However, increasing the reverse curve of Spee from 1 to 5 mm did not produce any further increase in arch length (Figure 1). Measurements to fixed points on the glass container revealed that the increases in arch length were due to a combination of mesial movement of the crowns of the incisors and distal movement of the crowns of the molars of similar magnitude.

Intercanine distance

In all the experiments, only very small changes in intercanine distance were noted, ranging from an increase in intercanine distance of 0.2 mm to a reduction of 0.9 mm (Figure 1). In most of the experiments very slight reductions (less than 1 mm) in the intercanine distance were recorded. Increasing the depth of the reverse curve of Spee in the archwire did not produce greater intercanine contraction or expansion.

Intermolar distance

The total changes in intermolar distance were also small and ranged from a slight reduction of 0.6 mm to an increase of 1 mm. The flat 0.018 × 0.025-inch stainless steel archwire, and those with a 1- and 2-mm reverse curve of Spee produced very small reductions in intermolar distance of between 0 and 0.6 mm (Figure 1). The archwires

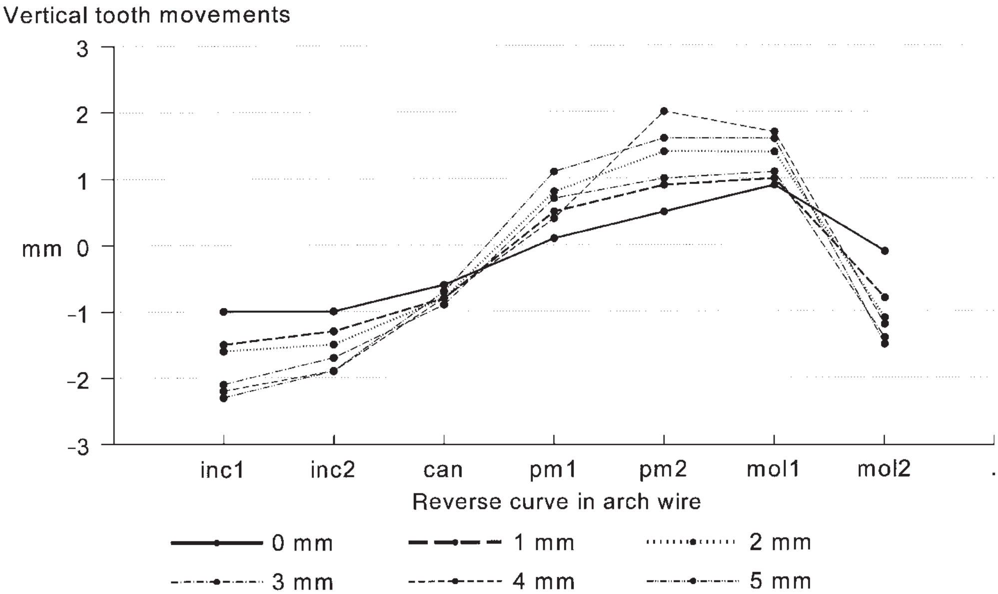


Figure 2 The vertical movements recorded for each tooth on the left side of the arch.

with 3-, 4-, and 5-mm reverse curves of Spee produced small increases in intermolar distance.

Vertical tooth movements

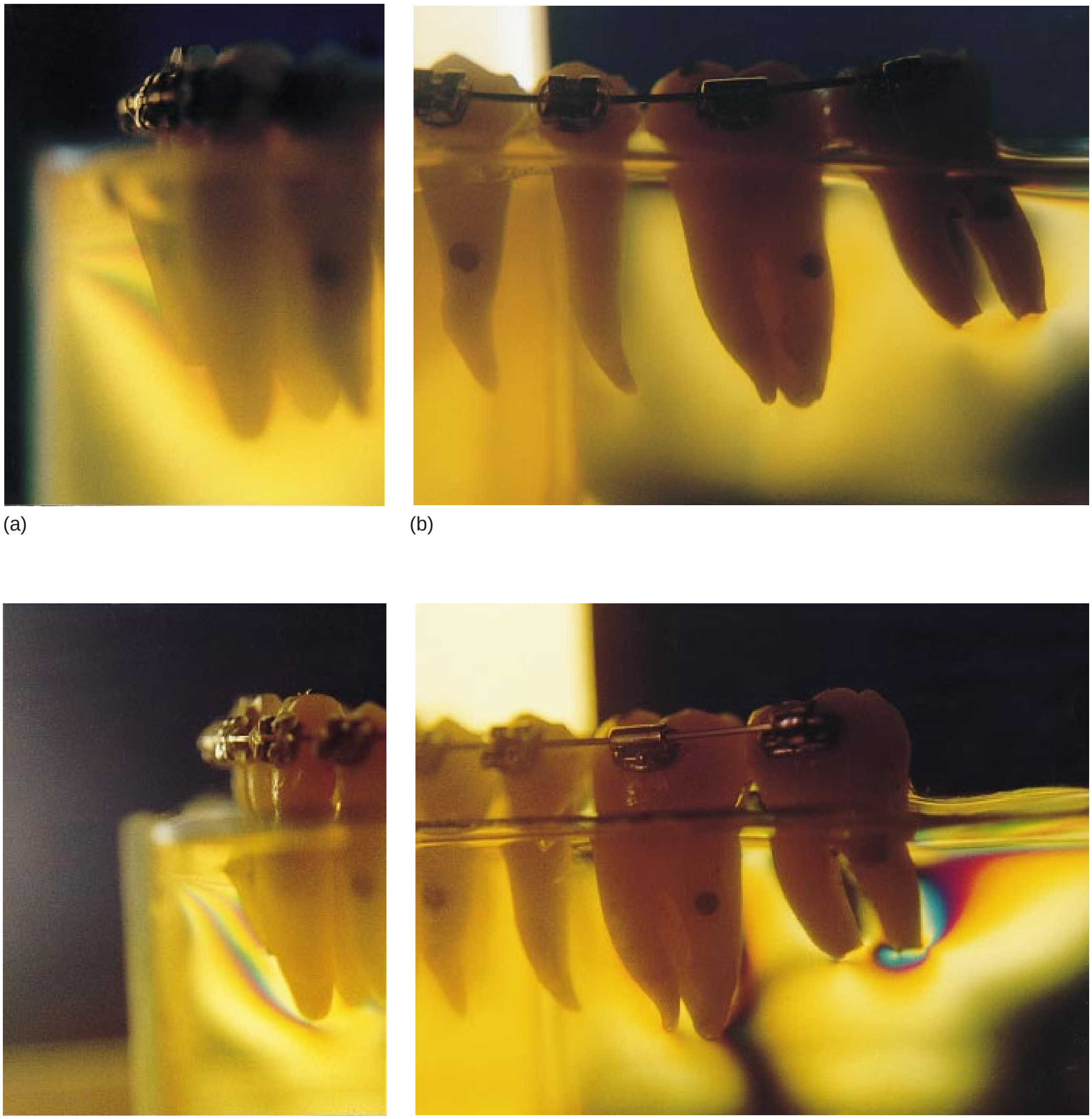
The total vertical movements of the crowns of the teeth on the left side of the arch for each archwire are illustrated diagrammatically in Figure 2. All the archwires produced a downward vertical movement in the crowns of the incisors, canines, and second molars. In all the experiments, the crowns of the first and second premolars, and first molars showed an upward vertical movement. Increasing the reverse curve of Spee in the archwire increased the vertical movements observed (Figure 2).

Incisor and molar rotational movements

Unfortunately, the overlap of the incisor and canine roots in the transverse plane meant that it was impossible to accurately measure the incisor root movements. However, the molar roots were clearly visible, and both the first and second molars demonstrated distal rotational movements. These rotational movements increased when the depth of the reverse curve of Spee was increased in the archwire. In all cases, the rotational movement of the molars was due mostly to mesial movement of the molar roots. Also, in all the experiments, the distal rotation observed was greater in the second molar than in the first molar. The flat 0.018 × 0.025-inch archwire produced distal rotations of 1 degree in the first molar and 6 degrees in the second molar. However, the 0.018 × 0.025-inch archwire with a 5-mm reverse curve of Spee resulted in a 6-degree distal rotation of the first molar and a 12-degree distal rotation of the second molar.

Photo-elastic analysis of the stress distribution

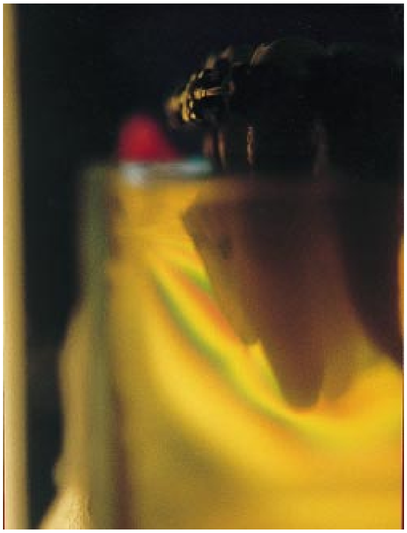
The typical photo-elastic fringe patterns observed are presented in Figure 3. This series of photographs illustrates the fringe patterns (stress distribution) around the roots of the teeth recorded at one hour. With the flat 0.018 × 0.025-inch stainless steel archwire, a small stress pattern was observed labial to the apical two-thirds of the incisors (Figure 3a,b). A very minor fringe pattern was also noted around the apices of the lower second molar. No fringe patterns were observed around the roots of the canines, premolars, or first molars.



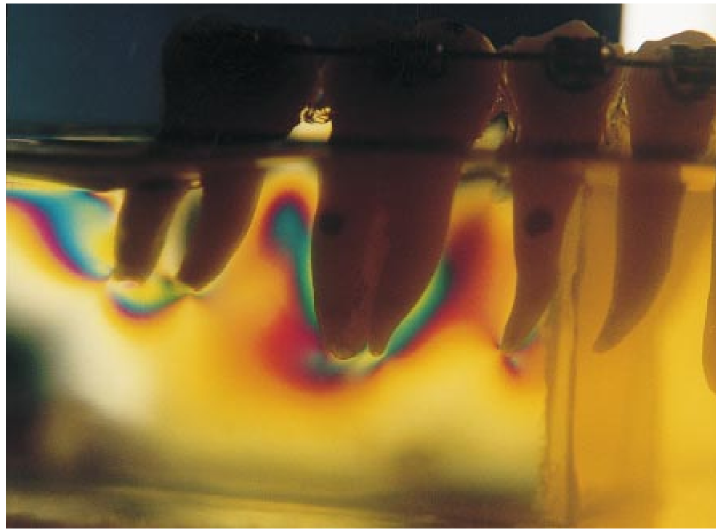
(a) (b) (c) (d)

Figure 3 The photo-elastic stress patterns recorded at 1 hour. (a) and (b) show the incisors and molars with a flat 0.018 × 0.025-inch stainless steel archwire fitted. (c) and (d) show the incisors and molars with a 0.018 × 0.025-inch archwire with a 1-mm reverse curve of Spee. (e) and (f) show the incisors and molars with a 0.018 × 0.025-inch archwire with a 5-mm reverse curve of Spee.

When a 1-mm reverse curve of Spee was placed in the archwire a more intense fringe pattern was found around the apical two-thirds of the lower incisors and canines, indicating that larger forces were being transmitted to the roots of these teeth (Figure 3c,d). The 1-mm reverse curve also produced a distinct fringe stress pattern on the distal root of the lower second molar and a minor fringe pattern around the roots of the first molar.



(e)



(f)

When the reverse curve of Spee was increased to 5 mm, the fringe pattern around the lower incisors increased further in size and extent, becoming more evident on the lingual and distal aspect of the incisor and canine apices. Increasing the reverse curve of Spee in the archwire also increased the size and extent of the stress patterns observed around the lower molars. Larger fringe patterns were noted around the roots of the lower first and second molars with the 5-mm reverse curve (Figure 3e,f). A small fringe pattern was also noted at the apex of the second premolar root. All these fringe patterns show that the roots of the incisors, canines, and molars experienced greater stresses when the reverse curve of Spee was increased in the archwire to 5 mm.

When viewed from above, no photo-elastic stress patterns were noted buccal or lingual to the canine, premolar, or molar teeth. Over the 9 hours of each experiment, all the stress fringe patterns that were observed diminished in magnitude and intensity until they completely disappeared due to the creep behaviour of the material.

Discussion

The dynamic nature of the photo-elastic gelatine model had a significant advantage over previous static *in vitro* orthodontic models, such as finite element analysis. Using this model, it is possible to monitor the stresses around the roots of the teeth as tooth movement occurs. In addition, compared with computer simulations, such as the finite element method, the *in vitro* model employed in the present study used real teeth, brackets, elastomeric modules, and archwires. However, in this photo-elastic model, alveolar bone was replaced by a gelatine mixture. This mixture exhibited a high level of steady creep (time-dependent deformation under loading), which permitted the teeth to move to a new position without elastic recovery. This unique property of the material meant that the orthodontic forces produced by the archwire could be completely dissipated over a 9-hour period. The photo-elastic properties of the gelatine mixture also allowed the longitudinal analysis of the changes in stress distribution around the roots of the teeth.

For any dynamic *in vitro* orthodontic model to be useful, the tooth movements observed should be similar to those that occur *in vivo*. It has to be accepted that the gelatine mixture is not a realistic representation of alveolar bone, and the teeth are not surrounded by soft tissues or subjected to occlusal forces. Care should therefore be taken when attempting to extrapolate these findings to the clinical situation. However, the direction of the tooth movements observed using the artificial gelatine model are similar to those reported in clinical studies. The *in vitro* model used in this study revealed that a continuous stainless steel rectangular archwire produced an apically-directed movement of the crowns of the incisors, canines, and second molar, and an occlusally-directed movement of the premolar and first molar crowns. It is unlikely that all of the apically-directed movements observed in the incisor and molar crowns can be attributed to true intrusion, but are due, in part, to mesial tipping of the incisors and distal tipping of the molars. This complex pattern of tooth movements mirrors exactly those observed clinically when using continuous archwires. Clinical studies have found that continuous archwires intrude incisors and canines (Mitchell and Stewart, 1973), extrude premolars and first molars when the second molars are bonded (Mitchell and Stewart, 1973; Bennett and McLaughlin, 1994; Parker *et al.*, 1995), and intrude second molars (Mitchell and Stewart, 1973). It has also been noted that lower second molars rotate distally as a lower curve of Spee is reduced (Bennett and McLaughlin, 1994).

The magnitude of tooth movement found in the present study is also similar to that observed clinically where continuous archwires have been used to level a lower arch. In a cephalometric study of 25 adult orthodontic patients, Weiland *et al.* (1996) found that levelling a lower arch with a continuous archwire resulted in an average lower incisor protrusion of 1.09 mm. In their study, the average lower incisor intrusion was 1.03 mm and the mean molar extrusion 1.3 mm. In the present study, the magnitude of arch length increased, and the vertical movements observed in the incisor and molar crowns were also in the 1–2-mm range.

No consensus exists about the effect on arch length when an increased curve of Spee is levelled.

It has been suggested that the clinician should allow for a 1-mm increase in arch length for every millimetre reduction in the curve of Spee (Proffit and Ackerman, 1986). However, recent work by Braun *et al.* (1996), using study models and a sophisticated measuring device, refuted this popular rule of thumb. The authors estimated that the space required to level a 9-mm curve of Spee would only require a 0.78-mm forward movement of the incisal edges of the lower central incisors. Some workers believe that the orthodontic mechanics used have a more dramatic effect on arch length than the space required to reduce a curve of Spee. It has been suggested that continuous archwires with reverse curves of Spee produce tipping forces on the lower incisors, which can lead to excessive protrusion (Woods, 1986; Braun *et al.*, 1996). The results of the present study fail to support this theory. Whilst arch length increased slightly when a flat archwire was fitted, little further change in arch length was observed when increasing reverse curves of Spee were placed in the archwire. It had been expected that increasing the reverse curve of Spee in the archwire would increase the downward and forward pressure on the incisor brackets, producing greater proclination of the lower incisor crowns and increasing arch length. It is interesting to speculate why arch length did not increase as the reverse curve of Spee was increased in the archwire. One possible explanation might be that when levelling archwires with reverse curves of Spee are placed, a reciprocal anchorage situation is created between the anterior and posterior teeth. Space is required to level the curve of Spee and the elevation of the teeth in the middle of the arch provides the impetus to overcome the frictional forces acting between the archwire and all the brackets such that arch length increases. This increase in arch length produces both distal tipping of the molars and anterior tipping of the incisors. However, once this space requirement is met the frictional forces acting between the archwire and the brackets may reduce the tendency for any further increase in arch length. Instead, the forces generated by increasing the reverse curve of Spee in the archwire are transmitted as a combination of intrusive and torquing forces to the roots of the incisors and molars, encouraging lingual movement of the incisor roots and mesial movement of the molar roots. The photo-elastic analysis appears to support this hypothesis, with the photo-elastic stress patterns becoming more intense around the roots of the incisors and molars as the reverse curve of Spee was increased in the archwire. In the incisor region, the stress patterns were more evident around the apices of the incisors as the reverse curve of Spee increased, indicating a more apically-directed force. Although it proved impossible to accurately measure the root movements of the incisor teeth in the present study, observation of the roots of the molar teeth revealed that they moved mesially as the reverse curve of Spee was increased. This stress distribution generated by levelling archwires might, in part, explain why root resorption is more common in mandibular incisors and first molars following fixed appliance treatment (Brezniak and Wasserstein, 1993).

Arch width measurements were taken to determine if flattening a curve of Spee affected the positions of the teeth in the transverse plane. Only minor changes in arch width were detected, which did not increase in magnitude as the reverse curve of Spee was increased in the archwire. The photo-elastic analysis also failed to reveal any evidence of major stress patterns acting transversely across the arch. These results appear to indicate that providing a stainless steel archwire is customized to the original arch form, increasing the reverse curve of Spee in the archwire does not produce increasing amounts of arch width expansion or contraction.

Deciding the depth of reverse curve that should be placed in a lower archwire when reducing an increased overbite has always been difficult for the clinician. It is likely that many factors, including the original curve of Spee in the lower arch, should be considered. In the present study increasing the depth of the reverse curve of Spee in the 0.018×0.025-inch stainless steel archwire increased the degree of intrusion observed in the incisors, canines, and second molars, and increased the amount of extrusion observed in the premolar and first molar teeth. The results suggest that increasing the reverse curve in an archwire produces more efficient levelling. Increasing the reverse curve of Spee in the archwire up to a depth of 5 mm did not further increase arch length. Further studies are required to determine the effects of placing even larger reverse curves of Spee in archwires. In the light of these findings, the clinician should appreciate that increasing the depth of the reverse curve in an archwire places greater stress on the roots of the incisors and the molars, and perhaps a greater potential for root resorption.

Investigators comparing the techniques of photo-elasticity and finite element analysis suggest that both methods give comparable results (Farah *et al.*, 1973; deVree *et al.*, 1983). However, some workers consider the cost of finite element computer packages to be a major disadvantage (Darbar *et al.*, 1994). Although special materials are needed for the photo-elastic technique these are inexpensive compared with the finite element method. Additional advantages include the ability to examine the effects of orthodontic force application on an entire arch of teeth, as well as allowing the observation of the stress distribution as the teeth move. The photo-elastic model reported in this paper represents a novel and easily understood method of evaluating the complex dynamics of orthodontic tooth movement.

Conclusions

1. The tooth movements noted using the gelatine *in vitro* model were similar to those observed clinically.
2. A continuous 0.018×0.025-inch stainless steel archwire produced a small increase in arch length. Increasing the reverse curve of Spee in the archwire to 5 mm did not further increase arch length.
3. Increasing the reverse curve of Spee in the archwire to 5 mm produced minimal changes in arch width.
4. Increasing the depth of the reverse curve of Spee in a rectangular stainless steel archwire increased the stress patterns observed around the incisor and molar roots.

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