

# Effects on tooth movement of force delivery from nickel–titanium archwires

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**SUMMARY** The aim of this project was to determine the *in vivo* effects of tooth movement with nickel–titanium archwires on the periodontium during the early stages of orthodontic treatment. The extent of tooth movement, severity of gingival inflammation, pocket probing depth, gingival crevicular fluid (GCF) flow, and the amount of the chondroitin sulphate (CS) glycosaminoglycan (GAG) component of the GCF of one maxillary canine in each of 33 patients treated with a pre-adjusted appliance were measured before and at four stages during the first 22 weeks of treatment. The methods involved the use of a reflex metrograph to determine the type of tooth movement and electrophoresis to quantitate the CS in the GCF.

It was found that GCF flow increased after 4 weeks of tooth movement whereas the increase in the amount of CS in the GCF, which is taken to be indicative of periodontal tissue turnover, occurred at the later stage of 10 weeks. Teeth which showed the greatest amount of tooth movement continued to express large amounts of CS in large volumes of GCF until 22 weeks, whilst the CS levels in those teeth moving to a smaller extent declined.

These data suggest that nickel–titanium archwires may produce a super-elastic plateau effect *in vivo* on canine teeth, which are initially displaced from the arch such that large amounts of tooth movement occur in the first 22 weeks of treatment.

## Introduction

Recent advances in orthodontic materials technology has resulted in the emergence of nickel–titanium archwires, which are called super-elastic. This terminology implies that an ideal archwire should exert the same force independent of the degree of activation (Burstone *et al.*, 1985; Drescher *et al.*, 1990).

There are two aspects of particular interest to the orthodontist regarding super-elastic archwires. If the archwires are limited from exerting excessive force, by their super-elasticity, undesirable side-effects, such as pain, root resorption, and hyalinization of the periodontal ligament should be eliminated. Secondly, if the force level remains above the physiological threshold required for tooth movement approximately all the way to total deactivation, a full alignment

should be attained without the necessity for frequent archwire changes.

*In vitro* experimentation has demonstrated that these archwires have failed to achieve super-elasticity; no plateau behaviour is exhibited unless there is excessive deflection (Segner and Ibe, 1995). There is, however, a current paucity of information regarding the *in vivo* effects of super-elastic archwires on the periodontium and, subsequently, on tooth movement itself. This study utilized a periodontal biomarker of tooth movement as an indicator of the effects of the archwire on the alveolar bone and periodontal ligament of the periodontium, and therefore on orthodontic tooth movement.

Research has been carried out that has detected glycosaminoglycans (GAG) in gingival crevicular fluid (GCF) samples in several clinical

situations: including endosseous dental implants (Last *et al.*, 1995), during orthodontic tooth movement (Last *et al.*, 1988), acute ulcerative gingivitis (Last and Embery, 1987), and sites of active periodontal disease (Last *et al.*, 1985; Waddington *et al.*, 1996).

The GAG chondroitin sulphate (CS) has been shown to be the predominant species in human alveolar bone (Waddington *et al.*, 1989) and this GAG composition is of particular importance, when the level of sulphated GAG present in a sample of GCF is interpreted as an indicator of active turnover of the deeper periodontal tissues.

Several studies have employed the model system of stimulated tooth movement to investigate further the GAG species in GCF quantitated by electrophoresis. A cross-sectional quantitative investigation of GAG in GCF demonstrated increased GCF volumes and CS levels from teeth undergoing orthodontic tooth movement compared with untreated controls. Both GCF flow rate and CS levels were increased in the samples taken from the gingival margin adjacent to the direction of tooth movement (Last *et al.*, 1988). Longitudinal studies on GCF and its GAG components before and during orthodontic treatment with fixed appliances have shown that the increase in GCF flow observed during treatment was only in part due to increased gingival inflammation (Samuels *et al.*, 1993). Changes in GCF flow and GAG composition around a canine tooth over a 2-year period of orthodontic treatment have shown a decrease in both GCF flow rates and GAG concentrations at the end of active tooth movement (Pender *et al.*, 1994).

These studies suggest that the CS proteoglycan present in GCF may be used as a marker for active bone and periodontal ligament turnover, and the detection of such a 'biomarker' represents a useful advance in the monitoring of the metabolic activity of the periodontal tissues during orthodontic treatment.

By using such changes in the volumes and CS content of GCF samples as indicators of periodontal tissue change, this study aimed to investigate the longitudinal effects of nickel-titanium archwires on tooth movement during the initial stages of fixed appliance treatment.

## Subjects and methods

### *Study group*

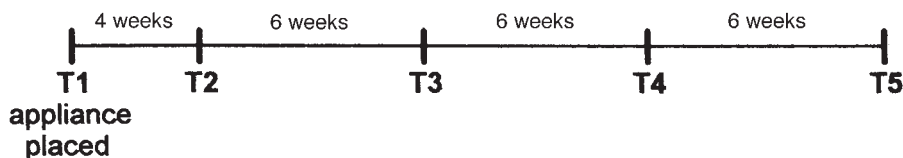
A cohort of 33 consecutive patients, average age 13.6 years (range 11.5–33), attending for the start of orthodontic treatment were recruited (16 males and 19 females). All the patients were treated by the same clinician (PDB) using a  $0.022 \times 0.028$ -inch pre-adjusted edgewise system (Straight Wire Appliance, 'A' Company, San Diego, USA), continuous archwires, and laceback mechanics. Initially, a 0.014-inch active austenitic nickel-titanium wire (Titinol™ Forestadent, Milton Keynes, UK) was placed in the upper arch and subsequently replaced with larger gauge nickel-titanium wire up to 0.018-inch active austenitic nickel-titanium in response to clinical requirements. One maxillary permanent canine was selected as the experimental tooth. There were eight non-extraction treatments and 27 patients with the first premolar extracted distal to the experimental canine. Extractions were performed 3 weeks before appliance placement.

Ethical approval was gained from the local ethics committee by submission of a protocol and a sample consent form. Subsequently, the patients and/or parents were fully informed of the nature of the investigation, and signed the consent form.

### *GCF collection and analysis*

The collection of GCF in this study was made in 2- $\mu$ l microcapillary tubes (Drummond Scientific Co., Pennsylvania, USA) placed at the gingival margin. The samples were collected during a timed period of 15 minutes. The GCF samples were collected from the mid-point between the most buccal point of the crown to the gingival margin and the most distal point of the crown to the gingival margin. The completed samples were transported over ice and transferred for storage in a freezer at  $-80^{\circ}\text{C}$ , to prevent any enzymatic degradation of the GAG components.

A total of five samples were taken during the investigation, i.e. one at the pre-treatment stage and four at intervals during the first 22 weeks of active treatment (Figure 1). The sample volume was calculated by measuring the length of fluid



**Figure 1** Stages (T1–T5) of GCF sample collection during the study period.

collected in each tube of uniform diameter and known total capacity.

The Gingival Index (Löe and Sillness, 1963) and pocket probing depths were recorded at the sampling site of the canine tooth in each case at the same visit as each GCF collection after collection had been completed. The probing depth was recorded using a force calibrated Prima Brontic graduated periodontal pressure probe set at 25 g probing pressure (Prima Instruments, Surrey, UK).

The GCF samples were applied to cellulose triacetate sheets (78 × 150 mm; Shandon Southern, Runcorn, UK). Electrophoresis was carried out in 0.2 M calcium acetate, pH 7.2, at 0.6 mA/cm width of the electrophoretic sheet. After 5 hours, the sheets were removed from the tanks and placed in a staining solution consisting of 0.05 per cent w/v Alcian Blue (8 Gx Gurr), in a solution containing 3 per cent w/v acetic acid and 0.05 M magnesium chloride, adjusted to pH 3.0 with sodium hydroxide. The staining period lasted for 15 minutes. Excess stain was then removed using a solution containing 1 per cent acetic acid and 0.05 M magnesium chloride, adjusted to pH 3.9.

A laser densitometer (LKB Bromma 2202 Ultrascan Laser Densitometer, Bromma, Sweden) was used to analyse the sample and the standard electrophoretograms on which the bands of separated GAG had been located with Alcian blue stain. By scanning the cellulose acetate sheets under the laser beam, an electrical signal conveying the stain intensity was finally transmitted to an integrator (LKB 2200 Recording Integrator, Bromma, Sweden), representing the signal graphically and, subsequently, as a numerical value.

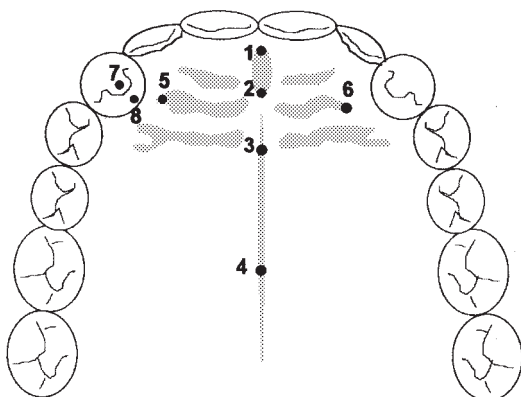
The amount of CS in the GCF sample was determined by comparing the test sample to a

standard GAG sample containing 100 ng of CS run on the same sheet. The identification of sample CS was accomplished by comparison with the known electrophoretic mobility of the band produced from the standard GAG sample.

#### *Determination of canine movement*

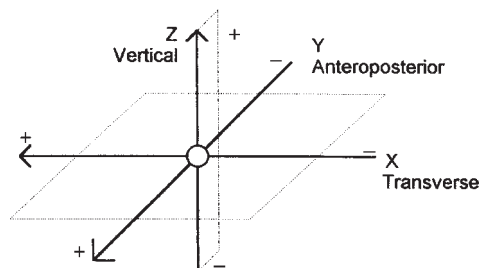
The distance moved by the canine tooth was measured with a reflex metrograph (Ross Instruments, Wiltshire, UK) on models cast from upper and lower alginate impressions taken before the commencement of active treatment and at 22 weeks. This method allowed analysis of the canine tooth movement in the transverse, antero-posterior and vertical planes of space during the study period. The definition of stable landmarks during fixed appliance therapy is problematic (Almeida *et al.*, 1995). However, fiducial points were selected from palatal landmarks on the rugae, which have been determined to be relatively stable during functional appliance treatment (Almeida *et al.*, 1995). Reproducible landmarks were also identified on the cusp tip and cingulum of the experimental canine. All the fiducial points were marked with a pencil point (Figure 2). Prior to the measurement of the models from the study, the recording of fiducial points from dental casts with the reflex metrograph was practised until repeat determinations were within 0.5 mm. The computer program written for use with the reflex metrograph included reference planes that were constructed utilizing the fiducial points (Figure 3) to make a horizontal plane based on points 2, 5, and 6, with point 2 being the zero origin, and a vertical plane based on points 2, 3, and 4, with point 2 being the zero origin.

The linear distances, in all three planes of space (Figure 3), moved by the canine during the study were calculated by subtracting the



**Figure 2** Fiducial points on maxillary study casts for reflex metrography. Point 1: the most anterior point of the incisive papilla. Point 2: the most posterior point on the incisive papilla. Point 3: a point on the mid-palatal raphe. Point 4: a point posterior to point 3 on the mid-palatal raphe. Point 5: the most lateral point on the second palatal ruga adjacent to the experimental canine. Point 6: the most lateral point on the second palatal ruga on the contralateral side to the experimental canine. Point 7: the cusp tip of the experimental canine. Point 8: a point on the palatal aspect of the experimental canine.

obtained post-treatment co-ordinates from those of the pre-treatment, in relation to the reference planes (Figure 3), with point 2 (Figure 2) being the constant zero origin. The angular change of the canine in the antero-posterior plane was calculated to differentiate bodily movement of the canine from tipping movement. The pre-treatment angle ( $\theta_1$ ) and the post-treatment



**Figure 3** Diagrammatic representation of the axes of canine tooth movement and their nomenclature used in reflex metrography.

angle ( $\theta_2$ ) were ascertained by antero-posterior and vertical co-ordinates. The angular change of the canine ( $\theta$ ) was resolved using the formula:

$$\text{Arc tan } \theta = (7Z_1 - 8Z_1)/(7Y_1 - 8Y_1) - (7Z_2 - 8Z_2)/(7Y_2 - 8Y_2)$$

In this formula, pre-treatment Z co-ordinates (Figure 3) of points 7 and 8 (Figure 2) are expressed as  $7Z_1 - 8Z_1$ , and post-treatment Z co-ordinates (Figure 3) of points 7 and 8 (Figure 2) are expressed as  $7Z_2 - 8Z_2$ . Y co-ordinates are similarly treated.

#### Data analysis

All the data were stored and analysed using SPSS (SPSS Inc., Chicago, USA) for Unix, Release 5.0 (solaris 2.2). The cohort of 33 cases

**Table 1** Descriptive statistics for the study group of 33 canine teeth, recorded at the stages of before treatment (T1), 4 (T2), 10 (T3), 16 (T4), and 22 weeks (T5) into active treatment. Mean  $\pm$  SEM GCF volumes ( $\mu\text{l}/15$  min), median (interquartile range) CS contents (ng/15 min), median (interquartile range) Gingival Index (GI) scores, and median (interquartile range) pocket-probing depths (PPD) (mm). The Wilcoxon Ranked Sum *W* test compared values for GCF volumes and CS contents at stages of the study.

	T1	T2	T3	T4	T5
GCF volume	1.0 $\pm$ 0.3 <sup>1,2,3,4</sup>	2.5 $\pm$ 0.3 <sup>1</sup>	2.9 $\pm$ 0.4 <sup>2</sup>	3.2 $\pm$ 0.4 <sup>3</sup>	3.2 $\pm$ 0.4 <sup>4</sup>
CS content	0 (0–0) <sup>5,6,7,8</sup>	5 (0–13) <sup>5,9,10,11</sup>	31 (10–70) <sup>6,9</sup>	29 (13–70) <sup>7,10</sup>	18 (5–49) <sup>8,11</sup>
PPD	1 (1–1.5)	1 (1–1.5)	1 (0–1.5)	1.5 (1.5–2)	1.5 (1.5–2)
GI score	0 (0–1)	1 (0–1)	1 (0–1)	1 (1–1)	1 (1–1)

The superscript numbers indicate the levels of significant difference achieved between stages sharing the same superscript, at  $P < 0.001$  (1, 2, 3, 4, 6, 7, 8, 9, 10) and  $P < 0.01$  (5, 11).

**Table 2** Categorization into three groups (small tip (ST), antero-posterior tipping (APT), and large tip antero-posterior and vertical (LTAPV)) of the canine movements (mm, mean  $\pm$  SEM) measured at the cusp tip, and the cingulum fiducial points in the anteroposterior, vertical and transverse planes, and the axial inclination change (degrees).

	ST <i>n</i> = 16	APT <i>n</i> = 9	LTAPV <i>n</i> = 8
Antero-posterior cusp tip	1.6 $\pm$ 0.3	4.0 $\pm$ 0.7	4.3 $\pm$ 0.6
Antero-posterior cingulum	1.5 $\pm$ 0.3	3.2 $\pm$ 0.7	4.0 $\pm$ 0.5
Vertical cusp tip	0.8 $\pm$ 0.2	1.7 $\pm$ 0.3	5.0 $\pm$ 0.3
Vertical cingulum	0.7 $\pm$ 0.1	1.2 $\pm$ 0.2	3.6 $\pm$ 0.5
Transverse cusp tip	1.9 $\pm$ 0.6	0.7 $\pm$ 0.2	1.7 $\pm$ 0.4
Transverse cingulum	1.7 $\pm$ 0.5	0.9 $\pm$ 0.2	0.9 $\pm$ 0.3
Axial change	4.9 $\pm$ 1.2	12.8 $\pm$ 1.8	27.0 $\pm$ 5.8

was analysed as a single group (Table 1), and also in three ways on the basis of the extent of different types of movement occurring in all three planes of space and axial inclination change (Table 2).

The values for the Gingival Index and pocket probing depths are represented as the median and interquartile range, as are the CS contents (ng/15 min). The GCF volumes ( $\mu$ l/15 min), are quoted as the mean  $\pm$  SEM. The significance of the changes occurring in the clinical variables between time points was calculated using the Mann-Whitney *U* or Wilcoxon Ranked Sum *W* test (two-tailed *P*). The significance of differences between the analysed groups with time was calculated by the Kruskal-Wallis one-way ANOVA test. Correlations between clinical variables were investigated by Spearman rank correlation coefficients.

## Results

For the 33 cases taken together (Table 1), GCF volumes (mean  $\pm$  SEM) increased significantly at the 4-week stage from the minimal pre-treatment flow of  $1.0 \pm 0.3 \mu$ l/15 min. The GCF flow at each sampling stage time from 4 to 22 weeks was significantly greater than the pre-treatment volume (Table 1). There were no significant differences in GCF flow between 4 and 22 weeks.

CS contents (median, interquartile range) of GCF samples also demonstrated a significant increase during the study, from an essentially undetectable content before the placement of fixed appliances to a maximum at 10 weeks into treatment of 31 (10–70) ng/15 min. A highly significant ( $P < 0.001$ ) increase in the CS contents occurred between 4 and 10 weeks into treatment, but there was no parallel increase in GCF flow over this period. The apparent decrease in CS contents at the 22-week stage (Table 2) from that found at the 10-week stage was not statistically significant. The amount of CS at 22 weeks was significantly greater than that found at both the pre-treatment ( $P < 0.001$ ) and the 4-week stage ( $P < 0.01$ ).

At the 4-week stage, following placement of fixed appliances (Table 1), there was an increase in both the level of gingival inflammation, as indicated by the median Gingival Index score and the mean pocket probing depth. However, in neither case was this increase statistically significant and no significant correlations were found ( $P > 0.05$ ) between gingival inflammation scores, and pocket probing depths with CS contents or GCF flow values.

The categorization of the movements of the canine teeth is shown in Table 2. The canine teeth were allocated to one of three groups: ST, APT, or LTAPV, on the basis of the nature and extent of tooth movement. The group ST ( $n = 16$ ), showed a small amount of axial change. Movements in the antero-posterior and transverse planes were on average less than 2 mm, with less than 1 mm of average change in the vertical plane. The principal movement produced in this group was small tipping (ST) of the crown. The APT group ( $n = 9$ ) showed small vertical and transverse change, more tipping than ST, and notable antero-posterior movement with more change at the cusp tip than the cingulum. Thus, this group is typified as showing antero-posterior tipping (APT). The LTAPV group ( $n = 8$ ) showed the largest variety and amount of tooth movement. These canine teeth showed large amounts of axial change, antero-posterior movement, and the greatest vertical extrusion. The average vertical movement of the cusp tip was greater than that of the cingulum, which is a



**Table 3** GCF volumes ( $\mu\text{l}/15$  min, mean  $\pm$  SEM) from canines in the three tooth movement groups (ST, APT, LTAPV) at the stages of pretreatment (T1), 4 (T2), 10 (T3), 16 (T4), and 22 weeks (T5) into active treatment. The Wilcoxon Ranked Sum  $W$  test compared values for GCF volumes at different stages of the study within each group. The Mann–Whitney  $U$  test was used for comparison between different groups at the same stage of the study. The superscript numbers and letters indicate the levels of significant difference achieved between either stages or groups sharing the same superscript, at  $P < 0.001$  (1, 2, 3, 4),  $P < 0.01$  (6, 7, A, C), and  $P < 0.05$  (5, 8, B). Significant differences between all stages of each group are demonstrated with the Kruskal–Wallis test.

	T1	T2	T3	T4	T5
ST	$0.5 \pm 0.2^{1,2,3,4,A}$	$2.6 \pm 0.5^1$	$2.3 \pm 0.4^2$	$2.6 \pm 0.5^{3,B}$	$2.4 \pm 0.5^{4,C}$
APT	$1.5 \pm 0.4^A$	$2.4 \pm 0.7$	$3.3 \pm 1.0$	$3.1 \pm 0.5$	$3.1 \pm 0.7$
LTAPV	$1.3 \pm 0.9^{5,6,7}$	$2.4 \pm 0.6^8$	$3.7 \pm 0.6^5$	$4.8 \pm 0.9^{6,8,B}$	$4.8 \pm 0.8^{7,C}$

$P < 0.001$ : 1, 2, 3, 4;  $P < 0.01$ : 6, 7, A, C;  $P < 0.05$ : 5, 8, B.

Kruskal–Wallis: in group 1, T1 smallest,  $P < 0.01$ ; in group 3, T1 smallest,  $P < 0.01$ .

further indication of tooth tipping. Thus, this group is characterized by large tipping, with anteroposterior and vertical movements (LTAPV). Of the 33 patients participating in the study, eight had non-extraction treatment. Of these, seven were in the ST group, which also included nine patients with first premolar extraction treatment. The average amounts of the different types of tooth movements, which occurred in the extraction and non-extraction subgroups of ST, were similar except for the amount of axial change. The extraction patients had an average of 4 degrees, whilst the non-extraction subgroup had 1 degree of axial change, but this difference was not statistically significant ( $P > 0.1$ ).

Table 3 shows the profiles of the volumes of GCF collected for each of the three tooth movement groups. In all groups, the smallest quantity of GCF was collected before the placement of the orthodontic appliance and, at this stage, the ST group showed a smaller GCF flow than the APT group ( $P < 0.01$ ). The GCF flow for ST increased at 4 weeks ( $P < 0.001$ ) and remained relatively constant thereafter. All sample collections during treatment were significantly greater than the pre-treatment flow. The APT group followed a trend of increasing GCF flow with time, which had doubled by 10 weeks and remained constant up to 22 weeks. However, these increases on the pre-treatment flow were not statistically significant. The GCF flow in

the LTAPV group increased over the period of the study with a significantly greater flow at 10, 16, and 22 weeks than at the pre-treatment stage. The mean flow at 16 weeks was twice ( $P < 0.05$ ) the flow at 4 weeks. In addition, the flow in LTAPV was larger than ST at both 16 ( $P < 0.05$ ) and 22 weeks ( $P < 0.01$ ).

The profiles of the CS contents of the GCF samples found during the study in each of the tooth movement groups (Table 4) show that, notwithstanding the variability of CS content, all groups demonstrated an increase in CS after the application of an orthodontic force and the commencement of tooth movement. CS contents in the ST group increased from pre-treatment to 4 weeks ( $P < 0.001$ ) and from 4 to 10 weeks ( $P < 0.05$ ), but decreased from 10 to 22 weeks ( $P < 0.001$ ). This rise and fall in CS content of GCF contrasts with the relatively constant GCF flow after 4 weeks (Table 3) in this group. CS contents in the APT group increased from pre-treatment to 10 weeks ( $P < 0.001$ ) and from 4 to 10 weeks ( $P < 0.01$ ). At 16 and 22 weeks, the CS amounts were smaller than at 10 weeks but with a large range so that, although they were significantly elevated over pre-treatment levels ( $P < 0.05$ ), there was no significant decrease after 10 weeks. Again, the trend of falling CS contents after 10 weeks differed from the pattern of GCF flow which on average was greater than  $3 \mu\text{l}/15$  min between 10 and 22 weeks (Table 3). The

**Table 4** CS contents (median, interquartile range; ng/15 min) of GCF samples from canines in the three tooth movement groups (ST, APT, LTAPV) at the stages of pre-treatment (T1), 4 (T2), 10 (T3), 16 (T4), and 22 weeks (T5) into active treatment. The Wilcoxon Ranked Sum *W* test was used to compare values for CS contents at different stages of the study within each group. The Mann–Whitney *U* test was used for comparison between different groups at the same stage of the study.

	T1	T2	T3	T4	T5
ST	0 (0–0) <sup>1,2,3,4</sup>	0 (0–9) <sup>1,5,6,A</sup>	37 (9–72) <sup>2,5,7</sup>	26 (6–67) <sup>3,6</sup>	7 (0–30) <sup>4,7,B</sup>
APT	0 (0–9) <sup>8,9,10</sup>	12 (2–18) <sup>11,A</sup>	52 (25–100) <sup>8,11</sup>	29 (6–100) <sup>9</sup>	25 (5–52) <sup>10</sup>
LTAPV	0 (0–0) <sup>12,13,14</sup>	11 (0–36) <sup>15,16</sup>	21 (10–35) <sup>12</sup>	42 (18–58) <sup>13,15</sup>	43 (19–83) <sup>14,16,B</sup>

The superscript numbers and letters indicate the levels of significant difference achieved between stages or groups sharing the same superscript at:  $P < 0.001$  (1, 7, 8, 14, A);  $P < 0.01$  (6, 11, 12, 13, 19); and  $P < 0.05$  (2, 3, 4, 5, 9, 10, 15, 16, B).

Significant differences between all stages of each group are demonstrated with the Kruskal–Wallis test.

Kruskal–Wallis in ST: T1 smallest,  $P < 0.001$ ; T2 smaller than T3, T4, and T5,  $P < 0.01$ . In APT: T1 smallest,  $P < 0.01$ .

In LAPTIV: T1 smallest,  $P < 0.001$ ; T2 smaller than T3, T4, and T5,  $P < 0.05$ .

LTAPV group, which showed the most tooth movement, had a markedly different profile of CS content of GCF from the other tooth movement groups. In the LTAPV group, the CS content profile paralleled that of the GCF flow in that the amounts of CS were greatest at 16 and 22 weeks compared with the pre-treatment ( $P < 0.01$ ) and 4-week ( $P < 0.05$ ) samples. In addition, the CS amount at 22 weeks was significantly greater in LTAPV than ST ( $P < 0.05$ ).

## Discussion

This study has confirmed that orthodontic tooth movement is related to increases in both GCF flow and CS levels in GCF. However, these changes do not occur coincidentally. Generally, the GCF flow increased at a stage before marked increases in the CS amounts were detected. Furthermore, those teeth which demonstrated smaller amounts of movement, groups ST and APT, showed a tendency for reduced amounts of CS in their elevated GCF flow at 16 and 22 weeks, whilst the LTAPV group with the greatest tooth movement maintained high levels of CS in a significantly elevated GCF flow.

These increases in GCF flow and CS content are unlikely to be due to the effects of increased gingival inflammation as neither Gingival Index scores nor pocket probing depths changed significantly during the period of the study. The

observation that maximal CS contents of the GCF samples found in the tooth movement groups at the 10–16-week stage may reflect a delay between the application of an orthodontic force and the development of biochemical changes in the extracellular matrix of the perturbed periodontal tissues, manifest as increased CS levels in the GCF. In contrast, GCF flow increases markedly at the earlier stage of 4 weeks, which suggests that the earliest effect of the application of orthodontic force may be on the blood vessels of the periodontal tissues.

The tissue response evoked by the nickel–titanium wires appeared to differ between the various groups in the study. Those teeth moving small amounts, groups ST and APT, tended to show a reduction in the CS content of GCF towards the end of the study period. Although the ST group contained patients with both extraction and non-extraction treatments, the conjecture can be made that the small amounts of tooth movement recorded for these groups occurred at the start of the treatment period. However, because measurement of tooth movement was made by comparing tooth positions at the beginning and end of the study, the timing of the phase of tooth movement during treatment is unknown. In this study, the patients were not selected because their canine teeth were particularly displaced and the small amounts of canine movement required by the ST group, in

particular, represented the clinical requirement for those patients. The patients in LTAPV, however, needed much more change in the position of the canine. In this group, the nickel–titanium wires demonstrated a constant physiological effect on the periodontal tissues as indicated by the increases in CS content of GCF at each sampling stage. This observation suggests that the nickel–titanium wires in the LTAPV group demonstrated the long range of action and constant force delivery expected of archwires with super-elastic properties (Burstone *et al.*, 1985; Miura *et al.*, 1986). Therefore, despite the evidence that *in vitro* nickel–titanium archwires tend not to produce a super-elastic plateau effect during force delivery (Segner and Ibe, 1995), the *in vivo* evidence presented by this group in this study suggests that nickel–titanium archwires do cause a relatively constant periodontal tissue perturbation. It is noteworthy that the nickel–titanium archwires from the particular manufacturer used in this investigation have been defined by *in vitro* testing as having no pseudo-elastic properties (Segner and Ibe, 1995). The present study is consistent with the canines studied previously (Samuels *et al.*, 1993) in demonstrating that vertical tooth movement, the greatest extent of which occurred in the LTAPV group, produces greater amounts of CS in the GCF than predominantly horizontal movements.

The amount of movement measured between study models taken pre-treatment and after 22 weeks of treatment, in contrast with a previous study (Samuels *et al.*, 1993), allowed an assessment of the range and type of tooth movement in all planes of space, including axial inclination changes, using reflex metrography. The standard of 0.5 mm was more generous than the 0.4 mm of Gibbs and Hunt (1992), but it was sufficient to allow reliable discrimination to be made between the various subgroups. In the present study, reflex metrography was used to describe types of movement, rather than perform exact measurement. The amount of canine retraction over the 154 days of the study was, on average, 4.3 mm in the group with most retraction. Hasler *et al.* (1997) found 4.0–4.6 mm of retraction in 131 days. They also found differences in the rate of retraction, and axial change between

early and later extraction in the same patients. Although, the non-extraction patients in the present study showed no differences in the amount of tooth movement from those with extractions, there was a trend to greater axial change in the extraction patients. However, since the mechanics used by Hasler *et al.* (1997) were sectional, as compared with the fully banded continuous archwires of the present study, it is difficult to make comparisons.

## Conclusions

1. GCF flow is increased at 4 weeks, whilst the CS content of GCF is markedly increased after 10 weeks of orthodontic tooth movement with nickel–titanium archwires.
2. The CS content of GCF reduces after 10 weeks of treatment in those teeth with minimal movement, but continues to increase in those teeth which move large amounts.
3. By their continued expression of an increased level of a CS component of GCF, interpreted as a biomarker of sustained changes in the periodontal supporting tissues, those teeth demonstrating the greatest movements may show the constant response to force consistent with super-elastic effects of nickel–titanium wires.

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