sciendo

DOI: 10.2478/aoj-2006-0005

A clinical comparison between nickel titanium springs and elastomeric chains

Jim Bokas and Michael Woods

School of Dental Science, The University of Melbourne, Australia

Objectives: To compare the rates of maxillary canine retraction and molar anchorage loss when using either NiTi springs or elastomeric chains delivering a known force with sliding edgewise mechanics.

Methods: Twelve patients who required maxillary canine retraction into first premolar extraction sites as part of their orthodontic treatment were selected. In a split-mouth design, these patients received precalibrated NiTi springs (12 quadrants) and pre-measured elastomeric chains (12 quadrants), all delivering initial forces of approximately 200 g and being reactivated at 28 day intervals. Space closure and forward movement of the maxillary first molars were evaluated using maxillary impressions, which were taken before the start of canine retraction and then at 28 day intervals until canine retraction was almost complete.

Results: Statistical analysis revealed that the mean rate of space closure with NiTi springs (1.85 mm/month) was only 0.17 mm/month greater ($p = 0.011$) than that produced with the elastomeric chains (1.68 mm/month). The mean rates of anchorage loss for the NiTi springs and elastomeric chain were 0.46 mm/month and 0.45 mm/month respectively. This difference was not statistically significant. These amounts of forward molar movement were calculated to be between one quarter and one third of the average space closure per month, even in the presence of a fixed transpalatal arch.

Conclusion: The results indicate that the rates of space closure and molar anchorage loss using either NiTi springs or elastomeric chains, if reactivated every 28 days, are likely to be similar.

(Aust Orthod J 2006; 22: 39–46)

Received for publication: October 2005

Accepted: December 2005

Introduction

In contemporary orthodontic practice which involves the extraction of premolars, there is often a need to retract canines during space closure. Currently, when using sliding mechanics for canine retraction, the active force component may be delivered by applying closed nickel titanium (NiTi) coil springs or elastomeric chains.

Standard and superelastic NiTi closed coil springs are resistant to permanent deformation and produce relatively constant forces during deactivation.[1] Nevertheless, targeted force magnitudes for NiTi springs may not be the actual force magnitudes delivered under clinical conditions due to variations in product manufacturing and oral temperature.[2-4] In contrast, elastomeric chains which are composed of polyurethanes have been shown to lose approximately 50–75 per cent of their initial force over the first 24 hours. The force decay then becomes more gradual, resulting in approximately 30–40 per cent of the original force remaining after four weeks.[5–7]

Previous clinical studies have compared the effectiveness of NiTi springs and elastomeric chains during space closure.[8–11] However, these studies did not consider the applied force magnitude or the issue of anchorage loss during tooth movement. These are interesting oversights in view of the numerous human studies into clinically optimal orthodontic forces[12–16] and different strategies of anchorage control.[17–24]

Previous researchers have investigated the concept of clinically optimal orthodontic forces in human subjects during attempted bodily or tipping tooth movements and demonstrated varying rates of tooth movement with applied force magnitudes ranging from 40–250 g.[12–16] Quinn and Yoshikawa[25] conducted a critical review of the theories that relate orthodontic force to tooth movement and concluded that, 'the rate of tooth movement increases with increasing force up to a point, after which increasing forces do not result in an appreciable increase in tooth movement'. It has therefore been realised that a simple relationship between applied force magnitude

and the rate of orthodontic tooth movement does not exist.

Storey and Smith[12] specifically considered the relationship between the rate of tooth movement and applied magnitudes of force in humans. They observed maximum rates of tooth movement when forces in the range of approximately 150–250 g were applied during canine retraction. When the force was increased beyond this range, initially there was very little movement of the canines and instead, appreciable movement of the anchor teeth was seen. Begg[26] recommended the concept of differential forces in orthodontic treatment and 'light' forces were used between anterior and posterior units to control their respective movements. Many other strategies for anchorage control during orthodontic mechanotherapy have been discussed in the literature.[17–24] These include changes to extraction patterns, addition of teeth and/or various auxiliary devices to the anchorage unit, and modification of intra-arch retraction mechanisms. Such approaches fundamentally ensure that appropriate tooth movements and correct use of spaces are achieved during the management of extraction cases.

The present study was therefore designed to compare the rates of maxillary canine retraction and molar anchorage loss when using either standard NiTi springs or elastomeric chains delivering a known force with sliding edgewise mechanics.

Materials and methods

Patients from the Orthodontic Unit at the University of Melbourne, who required extraction of the maxillary first premolars and retraction of the canines as part of their treatment, were invited to participate in the study. Twelve healthy individuals (6 males, 6 females) ranging in age from 13 to 14.5 years participated. The patients' rights were protected, and the research protocol was approved by the Human Research Ethics Committee: HREC project No. 030082.

All patients were undergoing routine treatment with upper and lower fixed appliances, using pre-adjusted edgewise brackets and first molar bands with 0.018 x 0.025 inch slots/tubes. Following extraction of the maxillary first premolars, initial alignment was accomplished using a series of NiTi wires, taking an average of 6.8 months (range 5–8 months). Maxillary canine retraction was then carried out on a 0.016 x 0.016 inch stainless steel arch wire. Moderate anchorage was required for the patients in this study and passive removable 0.032 inch stainless steel transpalatal arches were attached to the maxillary first molar bands. In a split-mouth design, each patient received a precalibrated (standard) closed coil NiTi spring (Nitinol, 3M/ Unitek, Monrovia, CA, USA) in one maxillary quadrant and a premeasured 2-loop length of elastomeric chain (Alastik, 3M/Unitek, Monrovia, CA, USA) in the other maxillary quadrant. All devices were activated to deliver an initial force of approximately 200 g for canine retraction.

This study employed a computer-assisted measurement system to gather and process data on the physical properties of the devices to be used to deliver the force.[27] A universal testing machine, with a crosshead speed of 20 mm/min and a 10 kg load cell, was used to measure the relationship between the force and length of the springs and chains prior to their use in this study. To simulate the clinical loading conditions during testing, two customised hooks were fitted to the universal testing machine and one end of each NiTi spring and elastomeric chain was attached to one hook and the alternate end of each spring/chain was attached to the second hook with 0.009 stainless steel ligature wire tie. The samples were activated from their passive positions to 20 mm for the NiTi springs and to 9 mm for the elastomeric chain and then deactivated to the passive position. These amounts of activation were within the manufacturer's recommended guidelines for use.

The rate force data was recorded in newtons at 1 second intervals, digitised and stored by an IBM compatible computer fitted with an analog-to-digital interface board and associated data analysis and plotting software. The force activation – deactivation curves included the 200 g range for both NiTi springs and elastomeric chains (Figure 1). Forces given in newtons (N) were converted to grams (g) by multiplying the data by 100 x 1.0197.[4] All testing was performed at room temperature (25°C) and dry air conditions.

In total, 12 standard NiTi springs (9 mm) from the same batch were precalibrated using this method and stored individually until required. For the elastomeric chain, 5 successive 2-loop segments (5 mm) from a single spool were carefully cut using a sharp ligature cutter. A straight haemostat was used to

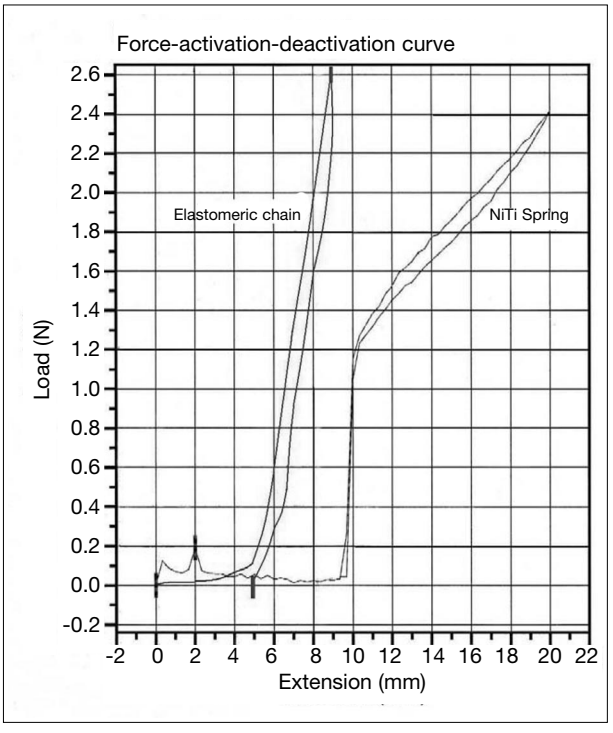


Figure 1. Typical force activation – deactivation curves for the NiTi springs and elastomeric chains.

handle the end of each sample. This was repeated 12 times, thus providing 12 sets of five 2-loop chains. The first 2-loop elastomeric chain from every set was placed in the universal testing machine to produce the force activation – deactivation curve. This approach avoided the use of a prestretched elastomeric chain that would not deliver exactly the same force as one applied for the first time.[28] The remaining pre-measured, unstretched 2-loop chains were stored individually until required.

Prior to canine retraction a baseline maxillary arch impression was taken of each patient. The transpalatal arch was only removed during the impression procedure and wax was applied to block out the undercuts of the fixed appliances. A medium-bodied polyvinylsiloxane impression material and customised impression tray were used to take all impressions.

A precalibrated NiTi spring was placed on one side of the maxillary arch, and a 2-loop length of elastomeric chain on the other side at the beginning of canine retraction. These devices were allocated at random to the right and left sides for each subject

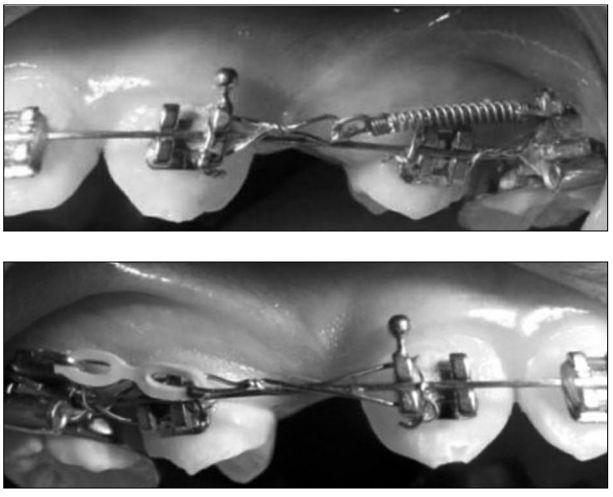


Figure 2. Clinical canine retraction using a precalibrated NiTi spring and a premeasured elastomeric chain (same subject).

(Figure 2). The precalibrated NiTi springs were attached by their eyelets to the first molar hooks and to the distal tie wings of the canine brackets by way of a 0.009 inch stainless steel ligatures. Each NiTi spring was extended 16 mm, which according to the force activation – deactivation curves delivered approximately 200 g of force. The elastomeric chains were attached similarly by their loops and extended 8 mm, which according to their premeasured force-extension curve delivered a force of approximately 200 g. The extensions of the NiTi springs and elastomeric chains were confirmed intra-orally three times using a customised calliper.

During canine retraction all patients were recalled for routine review at 28 day intervals. At each appointment oral hygiene was reinforced, the appliances were assessed for damage and an additional maxillary arch impression was made. At this time the NiTi spring was not replaced, but reactivated to deliver approximately 200 g of force and the decayed elastomeric chain was replaced with a new length of chain extended to deliver a similar force. All impressions were poured up in Velmix pink stone.

The study was discontinued one appointment before canine retraction had been completely achieved on either side of the arch. This ensured that the devices remained active for the duration of the study. In four subjects complete retraction was achieved in 56 days, in another four subjects in 84 days, and in the remainder the duration was 112 days. This resulted in

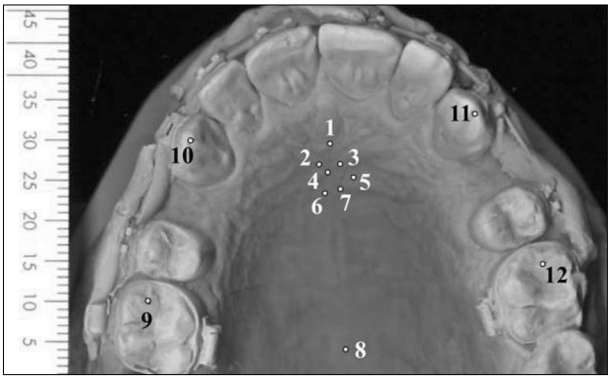


Figure 3. Scanned baseline maxillary cast marked for eight stable palatal landmarks and four occlusal landmarks.

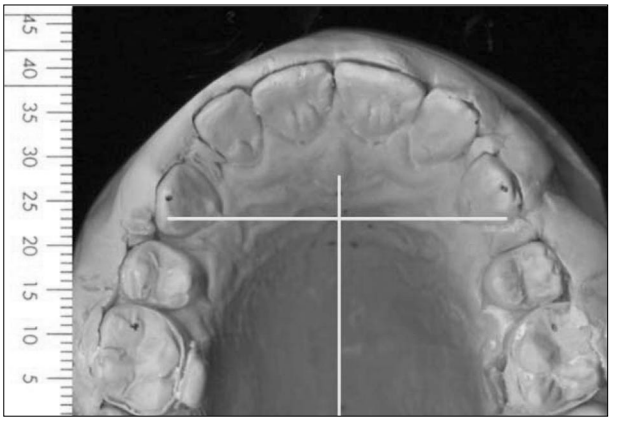


Figure 4. Scanned day 56 maxillary cast. Canine and first molar coordinates were based on the constructed reference lines formed by the Model-scan software after digitising.

48 maxillary dental casts being available for measurement, 12 of which represented baseline data.

Measurement of canine and first molar movement

With the aid of a 10x stereomicroscope eight stable palatal reference points,[29,30] the tips of the canines and points on the occlusal surfaces of the first molars were marked on all casts (Figure 3). The models were scanned from an occlusal perspective, the resulting images printed and the points digitised with customised software. The software measured the distances in millimetres moved by the maxillary canines and first molars at 28 day intervals in relation to two constructed reference planes (Figure 4). The space closure for each side was determined, along with the amount of mesial movement of the first molars. All models were re-digitised and analysed three times one week apart. In order to eliminate inter-examiner variability, the same examiner (JB) provided all treatment and recorded all data.

To validate the method of calculating space closure by digitising the points on the scanned images space closure was also measured directly on the study models with needle point and digital callipers. The observer was blinded to the identity of the casts and the measurements were repeated three times and compared to the digitised results using a one sample *t*-test. The results showed that the measurements obtained with either method were not statistically different ($p = 0.485$).

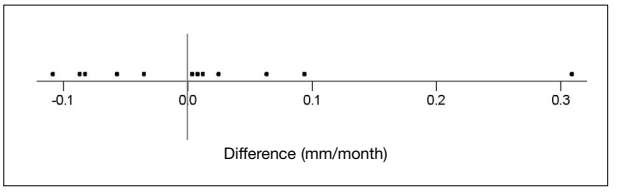


Figure 5. Plot representing the difference in rates of molar anchorage loss in each subject, observed when applying NiTi springs or elastomeric chains over 28 days.

All statistical analyses were prepared using the Minitab statistical software package for Windows. The average rates of space closure and mesial molar movement (mm/month) produced by the NiTi springs and elastomeric chains were calculated. Paired *t*-tests were used to compare the rate of space closure and mesial molar movement produced by the different methods of space closure.

Results

Table I summarises the rate of space closure. The maximum rate of space closure for the NiTi springs was 2.33 mm/month and 2.00 mm/month for the elastomeric chains. The minimum rate was 1.11 mm/month for the NiTi springs, and 1.15 mm/month for the elastomeric chains. The means for the springs and chains were 1.85 mm/month and 1.68 mm/month respectively. The mean difference between the rates of space closure produced by the two methods was 0.17 mm/month ($p = 0.011$).

Table I. Monthly rate of space closure obtained using either NiTi springs or elastomeric chains activated to 200 grams.

Variable	Sample	Maximum	Mean	Minimum
NiTi spring rate (mm/month)	12	2.33	1.85	1.11
Elastomeric chain rate (mm/month)	12	2.00	1.68	1.15
Rate difference NiTi – chain (mm/month)*	12	0.33	0.17	-0.04

* Paired *t*test, $p = 0.011$

Table II. Monthly rate of molar anchorage loss occurring when using either NiTi springs or elastomeric chains activated to 200 grams.

Variable	Sample	Maximum	Mean	Minimum
NiTi spring rate (mm/month)	12	0.81	0.46	0.24
Elastomeric chain rate (mm/month)	12	0.68	0.45	0.19
Rate difference NiTi – Chain (mm/month)†	12	0.13	0.01	0.05

† Paired *t*test, $p = 0.7$

Table II summarises the rate of molar anchorage loss. The NiTi springs were associated with a maximum of 0.81 mm/month forward molar movement whereas for the elastomeric chains the maximum forward molar movement was 0.68 mm/month. The minimum rates were 0.24 mm/month for the NiTi springs and 0.19 mm/month for the elastomeric chains.

The difference in the rates of forward movement of the molars in each subject are plotted in Figure 5. It appears that the differences are more or less evenly split between positive and negative values, suggesting that the two methods produce similar amounts of molar anchorage loss. The mean difference was 0.01 mm/month, which was not statistically significant ($p = 0.7$). On average, the NiTi springs and elastomeric chains produced a loss of anchorage of almost 0.5 mm/month. This is between a quarter and a third of the mean space closure per month.

Discussion

Previous studies that have compared NiTi springs to elastomeric chains are misleading because the initial forces were unequal and anchorage loss disregarded.[8–11] In the present study we ensured that the initial forces exerted by the springs and chains were the same, that they were applied over the same period and that molar anchorage loss was measured.

The results indicate that there was significant variability in both the rate of space closure and the molar anchorage loss. The importance of the biologic response and the individual variation in tissue reaction was reported by Reitan.[31] Hixon *et al.*,[32,33] agreed with Reitan[31] in that the individual variation in metabolic response was so great that it overwhelmed any differences caused by the force magnitude. They concluded that there was a large variation between patients, precluding the formulation of simple theories regarding force and anchorage.[33]

The force magnitude required to bodily move canines is estimated to range from as low as 100 g to as high as 300 or 350 g[34] and this force is thought to be dependant on the root surface area of the teeth being moved.[12,32] The force selected for retraction in this study was 200 g.

Using calibrated NiTi springs and carefully measured lengths of elastomeric chain to deliver an equal force for the same length of time is a significant advance over other studies in this area.[8–11] In fact, because of the large variation in the initial force levels produced by different elastomeric products and their variable force characteristics, the literature is confusing as to the amount of initial extension required to generate force levels compatible with efficient tooth movement. As a result several authors have recommended an initial over-extension of elastomeric chain to produce high initial force levels (approximately 400–450 g)[8] to compensate for the anticipated force decay.[6,35] Such force levels may seem excessive in view of the recommendations of Reitan,[31] who advocated lighter forces that would produce less extensive tissue hyalinisation and a more constant tissue remodelling. He recommended a force of 150–250 g for maxillary canine retraction. Quinn and Yoshikawa[25] surmised that a force between 100-200 g would be most efficient for canine retraction.

The small difference in rate of space closure observed in this study between the two different methods (0.17 mm/month; $p = 0.011$) is significantly less than that reported in the literature. Other studies have demonstrated that NiTi springs resulted in a significantly greater rate of space closure than elastomeric products.[8–10] However, it is difficult to reliably compare

the rates of tooth movement achieved in this study with the other studies, because different teeth and mechanics were used. It is perhaps reasonable to comment on the comparative findings. It might be that the significantly greater rates of tooth movement achieved with NiTi springs over elastomeric products in other studies could relate to the differences in the magnitude of the applied forces. High initial forces from elastomeric products, in anticipation of their inherent force decay, may have caused undue tissue hyalinisation and slower tooth movement.[12,31,25]

One could speculate that, at least over a 28 day period, the studied force systems are compatible with a clinically acceptable rate of tooth movement. Further studies to compare the rates of space closure using these methods over greater time intervals would be of interest. It is possible that significant differences in the rates of tooth movement with these techniques could be revealed if the duration between reactivations was increased.

Molar anchorage loss was a secondary question addressed in this study and it should be noted that transpalatal arches were attached to the maxillary first permanent molars throughout the study period. The results reveal that there is no statistically significant difference in the forward molar movement produced by precalibrated NiTi springs or premeasured elastomeric chains (p = 0.7). Previous studies comparing the two methods have not really considered the contribution to anchorage loss.[8–11] The mean rate of anchorage loss produced by both methods was approximately 0.5 mm/month. This amount of forward molar movement was calculated to be between a quarter and a third of the average space closure per month which is comparable with the findings of Lotzof *et al.*,[36] who compared canine retraction using pre-adjusted brackets and applied a standardised force of 200 g delivered by elastomeric chains.

As a final comment, care should be taken when interpreting these results. All of the activation – deactivation curves used to control the applied force characteristics of the NiTi springs and elastomeric chains were obtained at room temperature. It has been suggested that fluctuations in temperature, which would occur with the consumption of different foods and beverages, may affect the force delivery profile of elastomeric chains[37,38] and NiTi springs, especially superelastic springs.[4] Standard NiTi springs were used in this study instead of the superelastic springs to avoid the phase changes that occur in the latter during activation and deactivation[1,2] and temperature effects.[4] These features could have complicated precalibration of the NiTi springs and introduced error when interpreting the force curves used in this study.[4,39] While it was possible to limit the effects of temperature by using standard NiTi springs, the effects of temperature on the elastomeric chains could not be controlled.

Furthermore, the actual force applied in this study is difficult to determine for several reasons. The distribution of stress generated by the devices may be influenced by tooth morphology, root length and periodontal architecture.[40] Springs and elastics placed in the mouth are subject to uneven minor mechanical disturbances, for example during chewing that could repeatedly stretch and relax the spring or elastic.[27] Cyclic stretching of this kind might affect the average force as these devices become deactivated during at least part of the treatment time. In addition, the actual amount of force delivered to the teeth was likely to be less because of bracket/arch wire friction. Although stainless steel arch wires have been shown to generate the least amount of friction *in-vitro*,[41] factors such as the relative bracket/arch wire clearance,[42] tip and torque at the bracket/wire interface,[43] and even the force of ligation[44] may influence the frictional resistance. Lotzof *et al.*[36] stated that a frictional resistance of about 55 g would be created during sliding edgewise mechanics. Finally, despite the impact of specific material properties and friction within the system, the applied initial force could fall because both NiTi springs[45] and elastomeric chains deactivate as the teeth move closer together.[7]

Conclusions

Taking into account the limitations already outlined, the following conclusions may be drawn:

1. The rates of space closure using either precalibrated NiTi closing springs or premeasured elastomeric chains are likely to be similar. This would, however, seem to apply only if these devices were to be activated (and reactivated at intervals of 28 days) to deliver approximately the same clinical forces.

2. With the use of these two methods of force delivery, the amounts of molar anchorage loss (between a quarter and a third of the average space closure per month) are likely to be similar, even in the presence of fixed transpalatal arches.

Acknowledgments

The authors would like to thank Mr Geoffrey West for developing the Model-scan analysis program used in this research project and Ms Derchieh Hung, Statistical Consulting Centre, The University of Melbourne, for her help with the analysis of experimental data. The authors would also like to thank Dr Brian Lee for his considerable assistance in the undertaking of this work. This research was supported in part by a grant from the Australian Society of Orthodontists' Foundation for Research and Education.

No benefits in any form have been received or will be received from any commercial party related directly or indirectly to the materials used in this study.

Corresponding author

Professor Michael Woods
Orthodontic Unit
School of Dental Science
The University of Melbourne
720 Swanston Street
Victoria, 3010, Australia
Email: mgwoods@unimelb.edu.au
Tel: (+ 61 3) 9341 1497
Fax: (+61 3) 9341 1593

References

1. Miura F, Mogi M, Ohura Y, Karibe M. The superelastic Japanese NiTi alloy wire for use in orthodontics. Part III. Studies on the Japanese NiTi alloy coil spring. Am J Orthod Dentofacial Orthop 1988;94:89–96.
2. Melsen B, Topp LF, Melsen HM, Terp S. Force systems developed from closed coil springs. Eur J Orthod 1994;16: 531–9.
3. Manhartsberger C, Seidenbusch W. Force delivery of Ni-Ti coil springs. Am J Orthod Dentofacial Orthop 1996;109: 8–21.
4. Tripolt H, Burstone CJ, Bantleon P, Masnschiebel W. Force characteristics of nickel-titanium tension coil springs. Am J Orthod Dentofacial Orthop 1999;115:498–507.
5. Andreasen GF, Bishara S. Comparison of alastik chains with elastics involved with intra-arch molar to molar forces. Angle Orthod 1970;40:151–8.
6. Wong AK. Orthodontic elastic materials. Angle Orthod 1976;46:196–205.
7. De Genova DC, McInnes-Ledoux P, Weiberg R, Shayne R. Force degradation of orthodontic elastomeric chain: a product comparison study. Am J Orthod 1985;87:377–84.
8. Samuels RH, Rudge SJ, Mair LH. A comparison of the rate of space closure using a nickel-titanium spring and an elastic module: a clinical study. Am J Orthod Dentofacial Orthop 1993;103:464–7.
9. Sonis AL. Comparison of NiTi coil springs vs elastics in canine retraction. J Clin Orthod 1994;28:293–5.
10. Samuels RH, Rudge SJ, Mair LH. A clinical study of space closure with nickel-titanium coil spring and an elastic module. Am J Orthod Dentofacial Orthop 1998;114:73–9.
11. Dixon V, Read MJF, O'Brien KD, Worthington HV, Mandall NA. A randomized clinical trial to compare three methods of orthodontic space closure. J Orthod 2002;29: 31–6.
12. Storey E, Smith R. Force in orthodontics and its relation to tooth movement. Aust Dent J 1952;56:11–13.
13. Burstone CJ, Groves MH. Threshold and optimum force values for anterior tooth movement. J Dent Res 1962;39: 695.
14. Ziegler P. Ingervall B. A clinical study of maxillary canine retraction with a retraction spring and with sliding mechanics. Am J Orthod Dentofacial Orthop 1989;95: 99–106.
15. Daskalogiannakis J, McLachlan KR. Canine retraction with rare earth magnets: an investigation into the validity of the constant force hypothesis. Am J Orthod Dentofacial Orthop 1996;109:489–95.
16. Iwasaki LR, Haack JE, Nickel JC, Morton J. Human tooth movement in response to continuous stress of low magnitude. Am J Orthod Dentofacial Orthop 2000;117:175–83.
17. Higley LB. Anchorage in orthodontics. Am J Orthod 1969; 55:791–4.
18. Baker RW, Guay AH, Peterson HW. Current concepts of anchorage management. Angle Orthod 1972;42:129–38.
19. Hocevar RA. Understanding, planning, and managing tooth movement: orthodontic force system theory. Am J Orthod 1981;80:457–77.
20. Bennett JC, McLaughlin RP. Controlled space closure with a preadjusted appliance system. J Clin Orthod 1990;24: 251–61.
21. Roberts WE, Arbuckle GR, Analoui M. Rate of mesial translation of mandibular molars using implant-anchored mechanics. Angle Orthod 1996;66:331–8.
22. Wehrbein H, Feifel H, Diedrich P. Palatal implant anchorage reinforcement of posterior teeth: a prospective study. Am J Orthod Dentofacial Orthop 1999;116:678–86.
23. Janssens F, Swennen G, Dujardin T, Glineur R, Malevez C. Use of an onplant as orthodontic anchorage. Am J Orthod Dentofacial Orthop 2002;122:566–70.
24. Deguchi T, Takano-Yamamoto T, Kanomi R, Hartsfield JK Jr, Roberts WE, Garetto LP. The use of small titanium screws for orthodontic anchorage. J Dent Res 2003;82: 377–81.
25. Quinn RS, Yoshikawa DK. A reassessment of force magnitude in orthodontics. Am J Orthod 1985;88:252–60.
26. Begg RP. Differential force in orthodontic treatment. Am J Orthod 1956;42:481–510.
27. Han S, Quick DC. Nickel-titanium spring properties in a simulated oral environment. Angle Orthod 1993;63:67–72.
28. Nattrass C, Ireland AJ, Sherriff M. An investigation into the placement of force delivery systems and initial forces applied by clinicians during space closure. Br J Orthod 1997;24: 127–31.
29. van der Linden FPGM. Changes in the position of posterior teeth in relation to ruga points. Am J Orthod 1978;74: 142–61.
30. Bailey LT, Esmailnejad A, Almeida MA. Stability of the palatal rugae as landmarks for analysis of dental casts in extraction and nonextraction cases. Angle Orthod 1996;66: 73–8.
31. Reitan K. Some factors determining the evaluation of forces in orthodontics. Am J Orthod 1957;43:32–45.

32. Hixon EH, Atikan H, Callow GE, McDonald HW, Tracy RJ. Optimal force, differential force, and anchorage. Am J Orthod 1969;55:437–57.
33. Hixon EH, Aasen TO, Arango J, Clark RA, Klosterman R, Miller SS, Odom WM. On force and tooth movement. Am J Orthod 1970;57:476–8.
34. Boester CH, Johnston LE. A clinical investigation of the concepts of differential and optimal force in canine retraction. Angle Orthod 1974;44:113–9.
35. Rock WP, Wilson HJ, Fisher SE. A laboratory investigation of orthodontic elastomeric chains. Br J Orthod 1985;12: 202–7.
36. Lotzof LP, Fine HA, Cisneros GJ. Canine retraction: a comparison of two pre-adjusted bracket systems. Am J Orthod Dentofacial Orthop 1996;110:191–6.
37. Ash JL, Nikolai RJ. Relaxation of orthodontic elastomeric chains and modules *in vitro* and *in vivo*. J Dent Res 1978; 57:685–90.
38. Nattrass C. Ireland A, Sherriff M. The effect of environmental factors on elastomeric chain and nickel titanium coil springs. Eur J Orthod 1998;20:169–76.
39. Airoldi G, Riva G, Vanelli M, Fillipi V, Garattini G. Oral environment temperature changes induced by cold/hot liquid intake. Am J Orthod Dentofacial Orthop 1997;112: 58–63.
40. Tanne K, Sakuda M, Burstone CJ. Three dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofacial Orthop 1987;92: 499–505.
41. Kapila S, Angolkar PV, Duncanson MG Jr, Nanda RS. Evaluation of friction between edgewise stainless steel brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop 1990;98:117–26.
42. Frank CA, Nikolai RJ. A comparative study of frictional resistance between orthodontic bracket and archwire. Am J Orthod 1980;78:593–609.
43. Tidy DC. Frictional forces in fixed appliances. Am J Orthod Dentofacial Orthop 1989;96:249-54.
44. Sims APT, Waters ME, Birnie DJ, Pethybridge RJ. A comparison of the forces required to produce tooth movements in vitro using two self-ligating brackets and a pre-adjusted bracket employing two types of ligation. Eur J Orthod 1993; 15:377–85.
45. Angolkar PV, Arnold JV, Nanda RS, Duncanson MG. Force degradation of closed coil springs: an *in vitro* study. Am J Orthod Dentofacial Orthop 1992;102:127–33.