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ORIGINAL ARTICLE

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Rate of orthodontic tooth movement after changing the force magnitude: an experimental study in beagle dogs

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Structured Abstract

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Objectives – To study a possible dose–response relation between force magnitude and rate of orthodontic tooth movement by altering forces during bodily orthodontic tooth movement.

Setting and Sample Population – Eight young adult beagle dogs were used. The experiments were carried out in the Central Animal Facility, and all analyses were conducted in the Department of Orthodontics and Oral Biology, Radboud University Nijmegen Medical Centre.

Materials and Methods – Orthodontic appliances were placed exerting a reciprocal force on the mandibular second premolars and first molars. A force of 10 or 300 cN was randomly assigned to each side of the dogs. After 22 weeks, all forces were changed to 600 cN. Based on intra-oral measurements, tooth movement rates were calculated.

Results – The premolars showed no difference in the rates of tooth movement with 10 or 300 cN. Replacing 10 for 600 cN increased the rate, but replacing 300 for 600 cN did not. Molars moved faster with 300 than with 10 cN, and changing both forces to 600 cN increased the rate of tooth movement. Data from all teeth were pooled considering their relative root surfaces, and a logarithmic relation was found between force and rate of tooth movement.

Conclusions – Only in the very low force range, a positive dose–response relation exists, while in higher force ranges, no such relation could be established.

Key words: animal experimentation; dogs; force magnitude; orthodontics, corrective; tooth movement

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Introduction

Orthodontic tooth movement has been defined as the result of biological responses to interference in the physiological equilibrium of the dentofacial complex by an externally applied force (1). However, the quest for the optimal orthodontic force has not yet come to an end. The classical theory on this interplay is the pressure–tension theory that states that the application of an orthodontic force generates a 'pressure side' and a 'tension side' within the periodontal ligament. (2). The existence of such differential pressures has been questioned since then, and the biological focus has been shifted to the initiating effect of cellular strain and the subsequent cell biological processes (3–8).

In clinical orthodontic research, however, the search for the optimal force continues not only because of efficient tooth movement but also because of unwanted side effects such as root resorption. In a study on root resorption using a buccally directed force of 25 or 225 cN to premolars, it was found that the mean extent of tooth movement in the heavy-force group was almost twice as much as in the light-force group (9). In another study of the same research group with a split-mouth design for canine retraction where each patient received either 50 or 300 cN at a side, the amount of tooth movement in the initial phase was not related to force level, but at later stages, it was (10). Other clinical studies, in which forces of 50, 100, and 200 cN were used for buccal tipping of human premolars, showed the same rate of crown movement with 50 and 100 cN, but faster movement with 200 cN than with 50 cN (11, 12). Comparable findings have been reported from animal studies in beagle dogs, where forces as low as 10 and 25 cN were used. This resulted in a higher mean rate of bodily premolar movement with a force of 25 cN than of 10 cN, suggesting a dose–response relation for this force range (13). However, in a comparable model, it was shown that with higher forces, namely 50, 100, and 200 cN, no such dose–response relation could be established (14). These experimental data indicate that forces in the lower range initiate a dose-dependent response, while in the higher force range, the rate of tooth movement is not determined by the force magnitude. This might be explained by the fact that the higher forces all lead to a maximal rate of tooth movement. This suggestion is in agreement with the conclusions from a systematic literature study dealing with the force–tooth movement relation in humans and in animal studies (15). However, this review and the mathematical model (16) that was derived from the data conclusions were based on group means as data on individual differences were not available from existing studies.

A novel approach would be to study the effect of different forces on the rate of tooth movement within one individual. Therefore, the aim of this study was to evaluate the effects of deliberately changing force magnitude of low, moderate, and high forces within individual beagle dogs on the rate of tooth movement in the linear phase (14). The null hypothesis to be tested is that in the linear phase of orthodontic tooth movement, changing the force magnitude within an individual will not affect the rate of the tooth movement.

Materials and methods

Experimental set-up

A group of eight young adult beagle dogs (age 1–1.5 years) was used for this experiment. Ethical permission was obtained according to the guidelines for animal experiments of the Radboud University Nijmegen, the Netherlands.

All dogs had a complete permanent dentition. Mandibular third and fourth premolars and all premolars and the first molar in the maxilla were extracted. After 3 months, titanium implants were placed between the mandibular second premolar and the first molar on both sides. Again, 3 months later, orthodontic appliances were placed on the implants at the right and left side of the mandible to produce reciprocal bodily tooth movement of the second premolar and the first molar (Fig. 1). At the start of the experiment, a 10 cN force was exerted on one side of each animal, and a 300 cN force was used at the other side. The forces were assigned at random to either the left or right side. Direct intra-oral measurements were taken with a digital calliper once a week after the placement of the appliances. The forces were maintained for about 22 weeks, when all teeth were in the linear phase for a period of at least 1 month. Then, in seven dogs, the forces on both sides

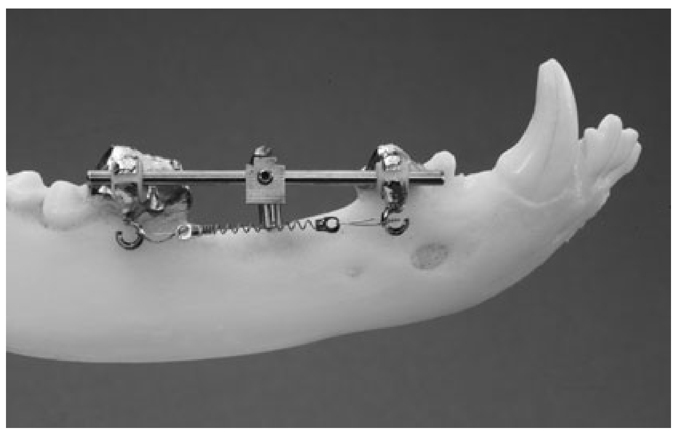

Fig. 1. Orthodontic appliance exerting a reciprocal force on the mandibular second premolar and the first molar.

were replaced by a force of 600 cN. In one dog, the forces of 10 and 300 cN were exchanged. Subsequent measurements were continued for 10 weeks to monitor changes in the rate of tooth movement.

Surgical procedures

Six months before the start of the experimental period, the dogs were premedicated with 1.5 ml Thalamonal® (fentanyl 0.05 mg/ml and droperidol 2.5 mg/ml; Janssen Pharmaceutica, Beerse, Belgium) and anaesthetized with 15 mg/kg Nesdonal® (thiopental sodium 50 mg/ml; Rhone-Poulenc Pharma, Amstelveen, the Netherlands). The mandibular third and fourth premolar on the left and right side were extracted after hemisection. The maxillary premolars and the first maxillary molar at both sides were also extracted to eliminate occlusal interferences. Healing of the extraction wounds was followed by intra-oral inspection on a weekly basis and radiography after 3 months. Then, custom-made titanium implants (10.0 mm long, Ø 3.0 mm) were placed in the mandible on both sides between the second premolar and the first molar. Again, 3 months later, incisions were made on top of the implants and a permucosal suprastructure was screwed on each implant.

Orthodontic procedures

Three months after the placement of the implants, separate alginate impressions (CA 37, Cavex Holland BV, Haarlem, the Netherlands) were prepared of the left and right mandibular arch after sedation by a subcutaneous injection of 1 ml of a generic preparation containing 10 mg oxycodon HCL, 1 mg acepromazine, and 0.5 mg atropine sulphate per ml. The impressions were poured out in stone (Silkyrock Violet, Whipmix Corp., Louisville, KY, USA) within a few hours. On the dental casts, an orthodontic appliance, allowing bodily distal movement of the second premolar and mesial movement of the first molar, was made of chrome–cobalt alloy (Wironium Bego, Bremen, Germany) (Fig. 1). Crowns with small buccal tubes were prepared on the second premolars and first molars. These crowns were cemented with Panavia Ex Dental Adhesive (Cavex Holland BV), and the custom-made permucosal part was screwed on top of the implant. A stainless steel sliding bar (Ø 2.0 mm) running through the buccal tubes of the crowns was secured on top of the permucosal part of the implant by a small locking screw. A sliding bearing made of a low-friction material (Pon LX®, Vink Kunstoffen, Didam, the Netherlands) was placed on the sliding bar within the tubes on the crowns. Then, these bearings were bonded to the crowns with Panavia Ex Dental Adhesive with virtually no resistance or axial play.

Forces were exerted by custom-made Sentalloy® closed coil springs of 10 or 300 cN (GAC International, New York, NY, USA). After 22 weeks, in seven dogs, the forces on both sides were replaced by a force of 600 cN. In one dog, the forces of 10 and 300 cN were exchanged. The superelastic springs exert a constant force over a wide range of activation (17, 18). They were attached from a buccal hook on the second premolar crown to a buccal hook on the first molar crown, resulting in a reciprocal force, inducing distal movement of the second premolar and mesial movement of the first molar.

Measuring procedures

Once a week, the distance between the reference points on the orthodontic appliance between the implant and the second premolar and between the implant and the first molar was measured intra-orally with a digital calliper. This technique has been shown to be accurate: in a previous study, the intra-observer difference was in the order of 0.01 mm and the SD of the mean differences between two observers was 0.02 mm (14). For each measurement, the dogs were sedated as described earlier, with a gradually increasing dose to 3 ml because of habituation. At each session, the appliance and the dentition were thoroughly cleaned with 1.0% chlorhexidine digluconate in water.

For each side of each dog, time–displacement curves were constructed for the premolar and the molar. The start of the linear phase was determined independently by two observers. Their scores were identical in almost all cases. In the few cases where a difference was found, a consensus was agreed. The rate of the tooth movement for a certain period was calculated as the slope of the time–displacement curve in the period under study.

For combining the data for the premolar and molar movement, the forces were recalculated in a new unit of force, the 'Premolar-centiNewton' (PcN), which was defined as follows: a PcN is the force that has the effect of a force of 1 cN on a mandibular second premolar. As a dog's mandibular first molar can be estimated to be ten times as big as a mandibular second premolar, a force of 1 PcN is the equivalent of 10 cN on a molar.

Statistical procedures

The means and standard deviations of the rate of tooth movement in the different experimental conditions were calculated. The correlation coefficients of the rate of tooth movement between premolars and molars at the same side in each dog were calculated by linear regression analysis. Differences in the rate of tooth movement between premolars and molars at the same side of a dog, the difference in the rate with 10 and 300 cN within each dog, and the effect of changing a force from 10 or 300 to 600 cN were all compared with paired *t*-tests. Differences were considered to be significant at $p < 0.05$.

After recalculation of the applied forces to PcN, a logarithmic curve fitting of the movement rates for the different forces was performed, and the explained variance was calculated.

Results

General aspects

Three months after the extractions, all wounds were completely healed without complications. The extraction sockets were filled with bony tissue of the same structure and density as the surrounding bone, as revealed by the radiographs. The surgical procedures for implantation proceeded uneventful. No complications were encountered, and all implants showed good stability after 3 months prior to the placement of the orthodontic appliances.

After removal of the orthodontic appliances, at the end of the experiment, none of the appliances showed distortions of the sliding bar.

Tooth movement

As reported earlier (13, 14), the individual time–displacement curves could be divided into four phases: an initial phase, a phase of arrest, a phase of increasing tooth movement, and a phase in which tooth movement took place with a constant rate, the so-called linear phase. In this study, only the linear phase was considered.

The mean rates and standard deviations of tooth movement of premolars and molars in the linear phase per force magnitude are summarized in Table 1. When subjected to identical reciprocal forces, premolars moved significantly faster than molars ($p = 0.03$) (Table 1, Fig. 2). However, large individual differences

Table 1. **Mean rates (μm/day ± SD) of linear tooth movement and their ranges for premolars and molars using different forces. Statistical analysis by paired *t*-tests**

		Rate of linear tooth movement				
		Premolar		Molar		Difference
Force	n	Mean ± SD	Range	Mean ± SD	Range	P – M
10 cN	9	28.6 ± 14.7	6–52	4.6 ± 2.1	0–7	$p < 0.01$
300 cN	9	32.6 ± 12.6	3–50	16.4 ± 13.1	5–46	$p = 0.03$
Diff 10–300		$p = 0.49$		$p = 0.02$		

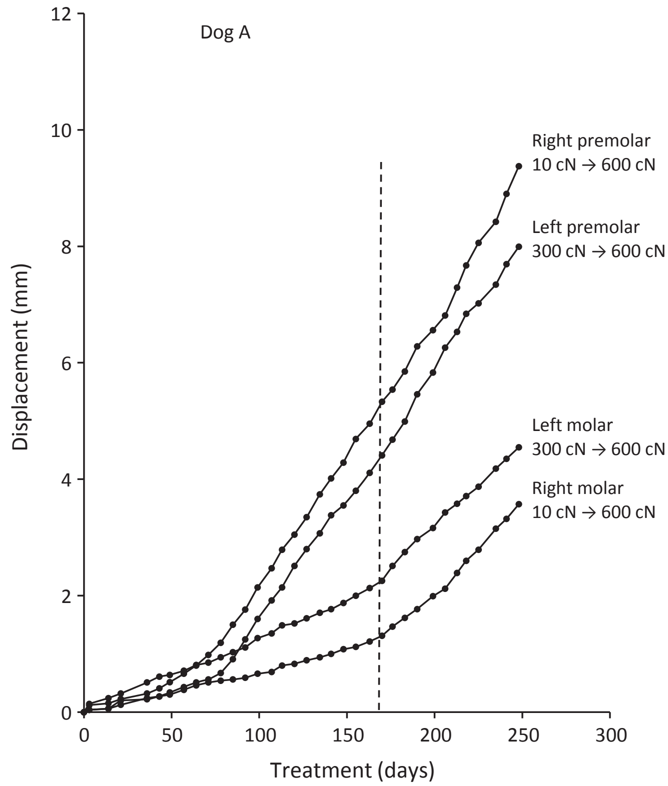

Fig. 2. Time–displacement curve of one dog (dog A) in which reciprocal forces were applied to the second premolar and the first molar. Initially, a force of 10 cN was applied at the right and 300 cN at the left side. After 24 weeks (dotted line) of active tooth movement, both forces were altered to 600 cN. Altering the force had no effect on the premolars, but it showed an increase in the tooth movement rate of the molars.

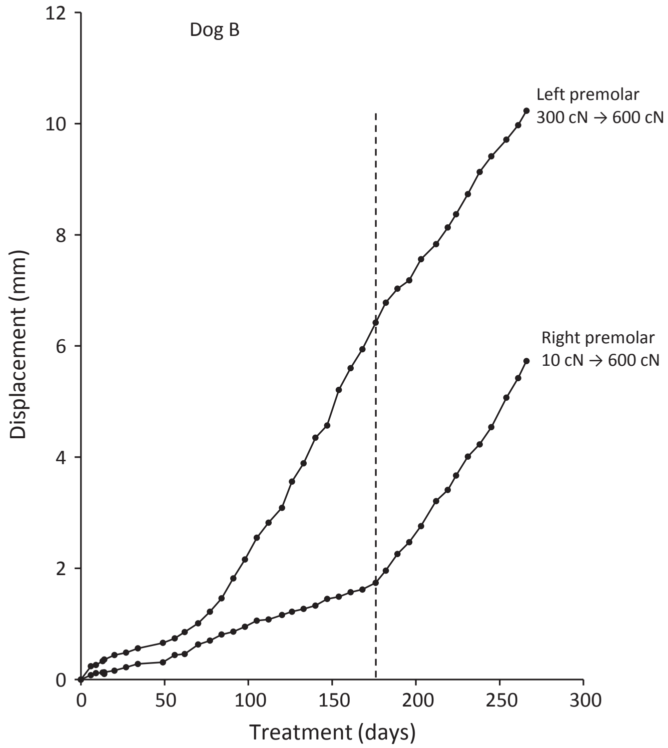

Fig. 3. Time–displacement curve of the premolars in one dog (dog B). Initially, a force of 10 cN was applied at the right and 300 cN at the left premolar. After 25 weeks (dotted line) of active tooth movement, both forces were altered to 600 cN. Altering the force from 10 to 600 cN increased the rate of premolar movement, but altering it from 300 to 600 cN did not.

were found as shown by the ranges (Table 1), and no significant correlation ($r = 0.118$, $p = 0.65$) could be found between the rate of premolar and molar movement within each dog. Comparison of the rates within each dog caused by 10 or 300 cN respectively showed the same rate of tooth movement for the premolars with both forces ($p = 0.49$), although this was not apparent in each dog (Fig. 3). The molars moved significantly faster with 300 than with 10 cN ($p = 0.02$) (Table 1, Fig. 2).

Changing the force on the premolars from 10 to 600 cN resulted in significant faster tooth movement ($p < 0.01$), but changing the force from 300 to 600 cN did not ($p = 0.60$). However, these rate changes showed a wide individual variation, and they were not apparent in each dog (Table 2, Figs 2 and 3). For the molars, it was found that both the change from 10 to 600 cN ($p < 0.01$) and the change from 300 to 600 cN ($p = 0.01$) resulted in a significant increase in the rate of tooth movement. Also for the molars, the changes showed a considerable individual variation, and the effect of force change was not established in all dogs (Table 3, Figs 2 and 4).

Pooling the data from the premolars and the molars after recalculating the force in PcN showed clearly a

Table 2. **Mean rates (μm/day ± SD) of linear tooth movement for premolars before and after changing the force and the mean individual changes in rate (μm/day ± SD) and their range. Statistical analysis by paired *t*-tests**

		Movement of premolars (μm/day) with different forces			Change in rate (μm/day)		
Forces	n	10 cN	300 cN	600 cN	Mean ± SD	Range	Difference
10 → 600 cN	7	27.1 ± 16.7		45.9 ± 5.8	18.7 ± 13.6	2 to 38	$p < 0.01$
300 → 600 cN	6		36.6 ± 7.6	34.2 ± 9.0	−2.2 ± 9.5	−15 to 11	$p = 0.60$

Table 3. **Mean rates (μm/day ± SD) of linear tooth movement for molars before and after changing force and the mean individual changes in rate (μm/day ± SD) and their range. Statistical analysis by paired *t*-tests**

		Movement of molars (μm/day) with different forces			Change in rate (μm/day)		
Forces	n	10 cN	300 cN	600 cN	Mean ± SD	Range	Difference
10 → 600 cN	7	4.6 ± 2.4		18.9 ± 7.8	14.3 ± 6.7	6 to 22	$p < 0.01$
300 → 600 cN	7		19.4 ± 13.5	34.3 ± 11.1	14.9 ± 11.1	−1 to 30	$p = 0.01$

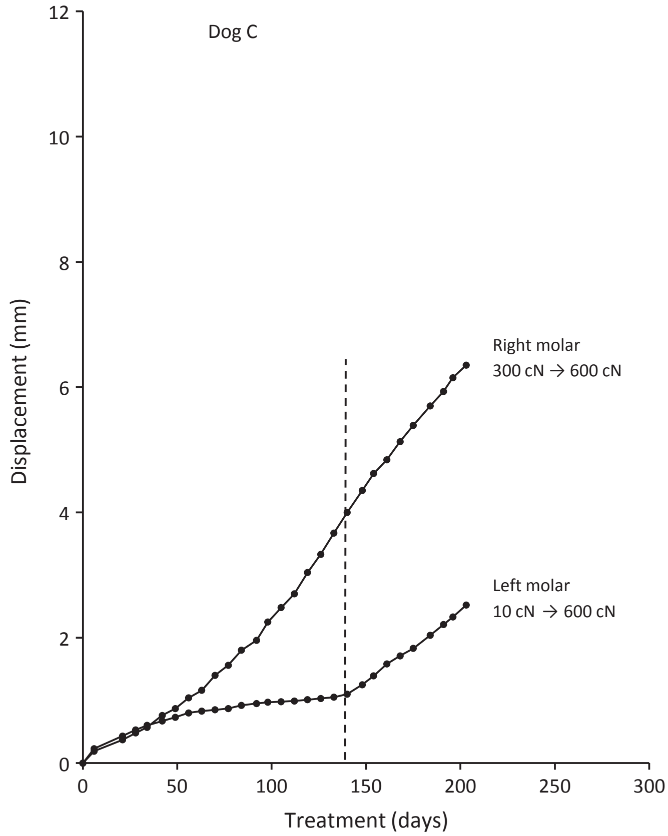

Fig. 4. Time–displacement curve of the molars in one dog (dog C). Initially, a force of 10 cN was applied at the left and 300 cN at the right molar. After 20 weeks (dotted line) of active tooth movement, both forces were altered to 600 cN. Altering the force from 10 to 600 cN increased the rate of molar movement, but altering it from 300 to 600 cN did not.

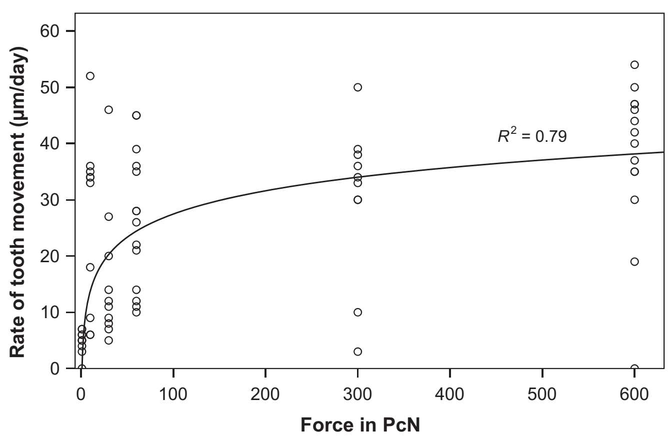

Fig. 5. Scatter plot of the rates of tooth movement of premolars and molars against force magnitude. Forces are recalculated in PremolarcentiNewtons. After logarithmic curve fitting, the relation showed an explained variance (R^2) of 0.79.

force-dependent rate of tooth movement (Fig. 5). Logarithmic curve fitting resulted in an explained variance (R^2) of 0.79.

Discussion

In this study, reciprocal forces were applied to second premolars and first molars in the mandibles of beagle dogs, and the forces were deliberately changed during the experimental period. Orthodontic tooth movement in dogs requires stout appliances that complicate the use of fragile springs. To overcome this problem, we applied reciprocal forces on the mandibular second premolar and first molar. This makes sense as periodontal stresses and strains are inversely proportional to the root surface areas. The surface area of the roots of a dog's mandibular first molar can be roughly estimated to be ten times that of a mandibular second premolar (unpublished data), suggesting that the application of a certain force on a first molar has about the same effect as the application of a ten times lower force on a second premolar.

In the present study, a novel crossover design was used in which sequentially in the same dog, the force was changed that enabled us to take into account individual variability. Furthermore, a modified dental implant was used as anchorage unit to overcome the effect of differential anchorage loss, which could not be excluded in other studies. This design might explain differences in results with earlier studies (9, 10, 19). Considering the movement of the premolars, it appeared that application of 10 or 300 cN within one dog had no significant effect on the rate of tooth movement (p = 0.49). These results can be interpreted as follows: forces of 10 or 300 cN induce tooth movement at the fastest possible rate because the biological system is unable to produce faster bone resorption. Therefore, the rate of tooth movement in this force range is independent of the force magnitude. Such a plateau in the dose–response curve was already suggested earlier (11, 13, 16, 20). It has been shown that a positive dose–response relation exists if dog premolars were moved with forces of 10 or 25 cN (13). However, in that study, the canine, fourth premolar, and first molar were used as anchorage. This could have lead to differential anchorage loss, and by that, to an overestimation of the tooth movement rates of the premolars. This problem has been overcome in the present study by the use of a mandibular bone implant for anchorage. Further analysis of the data from the present study indicated a small but significant increase in the rate of tooth movement if the force was changed from 10 to

600 cN ($p = 0.01$). On the other hand, if the force was changed from 300 to 600 cN, no such increase was found ($p = 0.60$). These results are in agreement with a study in rabbits that showed that in the initial phase, the daily rate of tooth movement was higher with a force of 60 cN than with 20 cN, but in the linear phase, no difference in daily rate was found (21). The same was found in a human study that showed that tipping forces of 50 and 100 cN resulted in the same rate of tooth movement, but a force of 200 cN resulted in faster movement than a force of 50 cN (11, 12).

The present study showed furthermore that the rate of tooth movement with a force of 10 cN is approximately 70% of the rate at 600 cN. Assuming that no tooth movement will take place without force application, these data suggest that the dose–response curve shows a steep increase at low force levels. The premolar results indicate that a force of 10 cN is sufficient to evoke stresses and strains within the periodontal ligament and the alveolar bone that lead to an almost maximal cellular reaction and bone remodelling (11–13, 22–24). Assuming that those stresses and strains evoked by a certain force vary inversely with the surface area of the roots, the effects of a reciprocal force on a second premolar and a first molar can be estimated.

In dogs, the surface area of the roots of a mandibular first molar is roughly ten times that of a mandibular second premolar (unpublished data). This suggests that a force of 600 cN on a first molar would evoke approximately the same cellular response as a force of 60 cN on a second premolar. Therefore, the force range from 10 to 600 cN on a molar would be equivalent to a force range from 1 to 60 cN on a premolar, and thus, completely within the relatively steep part of the dose–response curve. This idea is supported by the present data, because for the molars, a significant difference was found between the rate of tooth movement with 10 and 300 cN ($p = 0.02$). Furthermore, changing the force from 10 to 600 cN and from 300 to 600 cN both lead to a significant increase in the rate of tooth movement ($p \leq 0.01$).

That this rationale is correct is strongly suggested by Fig. 5. On the other hand, this figure is based on all individual data and does not explain the effect of individual differences. The individual variation is illustrated in Figs 2–4 of different dogs treated in an identical way, showing differences in the effects of altering forces. This is probably related to individual differences in bone morphology, surface area of the roots, and particularly, the biomechanical properties of the periodontal tissues (25). However, it can be concluded that the paired statistical analyses strongly suggest that the effect of changing the force magnitude within an individual is only apparent in the very low force range, while in higher force ranges, no such effect can be established.

Clinical relevance

There is an ongoing debate on the optimal force for orthodontic tooth movement. The general assumption is that a dose–response relation exists and that higher forces lead to faster tooth movement. Clinical studies, however, were unable to show such a relation to date. This study uses a novel experimental approach in beagle dogs. It evaluates the effects on the rate of tooth movement by changing the force magnitude within an individual. In the very low force range, faster tooth movement can be achieved by increasing the force, but in higher force ranges, this is not possible.

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