The relationship between the magnitude of a constant continuous orthodontic force and rate of bodily tooth movement was studied. In 25 young adult male beagle dogs, lower third premolars were extracted and bone markers were implanted in the mandible. Sixteen weeks later, an orthodontic appliance was placed, and elastics exerting 50, 100, or 200 gm were attached to the lower second premolar to produce bodily distalization. In each dog, different forces were used on the left and the right sides. As a control group, orthodontic appliances were placed without elastic on eight sides. Tooth movement was measured directly with a digital caliper twice a week during 16 weeks. Resulting curves could be divided in four phases. Large individual differences were found in the rate of tooth movement. Tooth movements on the left and right sides of each dog, however, were highly correlated. No significant differences in the duration of each phase nor in the mean rate of tooth movement during each phase were found between the three force groups. Maximum rate of tooth movement was about 2.5 mm per month in all force groups. There were no significant differences in the mesial movement of the anchorage unit between the force groups. It is concluded that under the circumstances of this study magnitude of force is not decisive in determining the rate of bodily tooth movement, but individual characteristics are. (Am J Orthod Dentofac Orthop 1996;110:16-23.)

In orthodontics, no consensus exists on how to move teeth most efficiently. An optimal approach should result in the highest possible rate of tooth movement without irreversible damage to the periodontal ligament, the alveolar bone, or the root. The formation of cell-free areas in the periodontal ligament cannot be avoided, even with light forces. Hyalinization occurs less frequently during bodily tooth movement than during tipping movements, because forces are more evenly distributed along the root surface during bodily movement.

In experiments using cats, large individual variations in the rate of bodily tooth movement were found after application of identical forces. These differences could be attributed to bone density, supraalveolar fibers, structure of collagen fibers, and cellular activity in the periodontal ligament. It was suggested that an optimal force range for tooth movement exists, related to the root surface area. Most interesting is the relationship between magnitude of pressure in the periodontal ligament and the rate of tooth movement. A linear relationship may exist up to a maximum rate of tooth movement that cannot be increased by further increase of force.

Experimental studies on tooth movement are often difficult to interpret because the description of orthodontic forces is not uniform and incomplete. Another problem is that in earlier studies particularly, tipping movements were investigated, where the tooth crown is used as a reference point for measuring tooth movement. The results of these studies are hard to interpret because the relation between the rate of crown and root movement is dependent on the position of the center of rotation that is difficult to determine and probably changes during tipping tooth movement.

Not only is the question of the relationship between the force magnitude per unit of root surface area and rate of tooth movement not answered, but equally important is a reliable registration of time-displacement curves of orthodontic tooth movement over a period longer than 4 weeks. This has never been done. The purpose of this experiment is to study the relationship between the magnitude of a constant and continuous orthodontic force and the rate of bodily tooth movement during a period of 16 weeks.
MATERIALS AND METHODS

Experimental set-up

A group of 25 young adult male beagles was used, including eight pairs of twin brothers and one triplet. The age of the dogs varied between 1 and 1.5 years. After extraction of the mandibular third premolars, bodily distalization of the lower second premolars was produced. The sides were divided into four groups: control sides (n = 7) in which the appliances were placed and no force was exerted and three experimental groups of sides in which 50 gm (n = 16), 100 gm (n = 14), and 200 gm (n = 14) was applied. In total, 44 sides were present in the experimental groups: one former control side (0 gm) was added to the 50 gm group, one to the 200 gm group, and on one side, the 200 gm appliance was lost. On the left and right sides of each dog, different forces were used which were selected at random (Table I).

Surgical procedures

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 anesthetized with Nesdonal 15 mg/kg (thiopental sodium 50 mg/mL; Rhone-Poulenc Pharma, Amstelveen, The Netherlands). The lower left and right third premolars were extracted after hemisection. Before the start of the experimental tooth movement, while the dogs were under general anesthesia, three tantalum bone markers (Ole Dich, Hvidovre, Denmark) were implanted on both sides of the mandible according to the method of Björk.11

Orthodontic procedure

Sixteen weeks after extraction of the third premolars, alginate impressions (CA 37, Cavex Holland BV, Haarlem, The Netherlands) of the lower dental arches were made after sedation with 1 mL of a preparation containing 10 mg oxycodeon HCl, 1 mg acepromazine, and 0.5 mg atropine sulfate, which was injected subcutaneous. The impressions were poured in stone (Silkyrock Violet, Whipmix Corporation, Louisville, Ky) within a few hours. On the dental casts, an appliance was constructed allowing bodily distalization of the second premolar (Fig. 1). Crowns were modeled in wax on the second and fourth premolar and onlays on the distal concave surface of the canine and the lingual surface of the permanent first molar. The canine, fourth premolar, and first molar were connected with a lingual bar to serve as an anchorage unit. The appliance was casted in a chrome-cobalt alloy (Wironium Bego, Bremen, Germany) and the inner surfaces were etched to improve retention. At the buccal side of the second premolar crown, a rigid sliding wire (316 chrome-nickel stainless steel) with a diameter of 2 mm was soldered. At the buccal side of the fourth premolar crown, a ring was modeled into which a round steel tube was glued (Uhu epoxy glue, Beecham, Milan, Italy). The inner diameter of the tube was 0.02 mm larger than the sliding wire at the second premolar. The mesial end of the sliding wire at the second premolar and the distal side of the buccal tube at the fourth premolar were prepared parallel to each other. They were used as reference planes for the measuring procedure.

While the dogs were anesthetized, the enamel was polished and etched, and the appliances were cemented with Panavia Ex Dental Adhesive (Cavex Holland BV, Haarlem, The Netherlands) at the left and right sides of each dog. During the experimental period of 16 weeks, elastics (Ormco Z-pak elastics, Glendora, Calif.) were attached from a buccal hook on the second premolar crown to a buccal hook on the fourth premolar crown. Because elastics show a great loss of force after initial extension, they were prestretched before experimental use. In this way, they kept a more constant force level for more than 2 weeks.12 Forces were measured twice a week with a strain gauge. New prestretched elastics were attached when a deviation of more than 5% of the desired force level was registered. The orthodontic appliance, teeth, and gingiva were thoroughly cleaned twice a week with a toothbrush and gauzes soaked with 0.02% chlorhexidine in water.

Radiographic procedure

Every 2 weeks, standardized oblique lateral radiographs of the left and right sides of the lower jaw were taken while the dogs were under general anesthesia. The dogs were fixed in a cephalostat according to Maltha13 with two earrods and a pin in the midsagittal plane. The x-ray film (Kodak dental x-ray speed photo, Kodak BV, Driebergen-Rijsenburg, The Netherlands) was placed in a standardized position, perpendicular to the central x-ray, at a distance of 5 cm behind the side of the mandible. The focus-film distance was 3 m. A Phillips Praxit X-ray machine (Philips, The Hague, The Netherlands) was used set at 20 mA, and 90 kV with an exposure time of 4 seconds. After exposure, films were processed in a R.P.X Processor (Kodak) for 90 seconds.

Measurements

Twice a week, the distance between the reference points on the orthodontic appliance was measured intraorally with a digital caliper. For each measurement, the dogs were sedated as described previously. Each time, three successive measurements were made, which

<table>
<thead>
<tr>
<th>Force</th>
<th>Side 1</th>
<th>Side 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>200</td>
<td></td>
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</tbody>
</table>

Table I. Number of dogs (n) with the forces (gm) applied to the second premolar on the left and right sides. Forces were selected at random for the left and right sides.
The means of the experimental and control (sham) groups of both doses were compared with Student's two-tailed t-test to detect any differences between the mean and standard deviation of the different groups. For each phase, Pearson correlation coefficients were calculated to determine the correlation between the dose and the movement of the second pronator and the medial epicondyle of the humerus during the muscle contraction.

The differences in the movement of the muscles at the head of the humerus and the standard deviation of the second pronator and the medial epicondyle of the humerus were compared using the independent samples t-test. A combined test was performed for each phase to determine the correlation between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction. The correlation coefficient was calculated between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction.

The differences in the movement of the muscles at the head of the humerus and the standard deviation of the second pronator and the medial epicondyle of the humerus were compared using the independent samples t-test. A combined test was performed for each phase to determine the correlation between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction. The correlation coefficient was calculated between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction.

The differences in the movement of the muscles at the head of the humerus and the standard deviation of the second pronator and the medial epicondyle of the humerus were compared using the independent samples t-test. A combined test was performed for each phase to determine the correlation between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction. The correlation coefficient was calculated between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction.

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The differences in the movement of the muscles at the head of the humerus and the standard deviation of the second pronator and the medial epicondyle of the humerus were compared using the independent samples t-test. A combined test was performed for each phase to determine the correlation between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction. The correlation coefficient was calculated between the muscle contraction and the movement of the mean and standard deviation of the muscle contraction.
RESULTS
General considerations

The measuring technique with the digital caliper was proved to be accurate, as the standard deviation of the mean difference between two observers was 0.02 mm. In the radiographic procedure, the error in distance B1-Q was 0.18 mm and intraobserver differences were negligible. The bone markers were proved to be stable as no significant change in distance B1-B2 was found. The weight curves showed a regular increase during the experimental period and a significant weight gain of 0.71 ± 0.93 kg was found ($p < 0.01$).

Tooth movement

Individual time-displacement curves were divided into four phases (Fig. 3). Transition from one phase to another in most instances was clear and scores of the two observers were mostly identical. Only for the transition from the acceleration phase (phase 3) to the phase of linear tooth movement (phase 4), differences of one or sometimes two measuring points were found. In these cases, a consensus was arrived at.

In Table II, the mean duration of phase 1, 2, and 3 is presented. In 75% of the cases, phase 1 lasted 3 or 4 days or less and its duration was never longer than 7 days. The arrest of tooth movement during phase 2 for all force groups lasted an average of about 7 days. In 27% of all cases, phase 2 was absent, and continuous tooth movement from the beginning to the end of the experiment was observed. In 23% of all cases, the acceleration of tooth movement during phase 3 lasted until the end of the experiment; these cases are not listed in Table II. No relationship was found between the duration of phases 1, 2, or 3 and the magnitude of the force (ANOVA, $p > 0.1$).

Between the force groups of 50, 100, and 200 gm, no significant differences in mean rate of tooth movement were found during any phase (ANOVA, $p \geq 0.1$, Table III). However, a positive correlation was found between the rate of tooth movement during phase 1 and the magnitude of the force (Pearson 0.33, $p < 0.05$). Mean total tooth movement during phase 1 was 195 μm for 50 gm and 280 μm for 200 gm. The combined $t$ test showed that no
Table II. Mean duration (days) and SD of the initial phase (1), phase of arrest of tooth movement (2), and acceleration phase (3) of the second premolar for forces of 50, 100, and 200 gm

<table>
<thead>
<tr>
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<th>SD</th>
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<th>Mean</th>
<th>SD</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
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</tr>
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<td>36.6</td>
<td>23.4</td>
<td>11</td>
<td>35.6</td>
<td>21.6</td>
<td>10</td>
<td>38.2</td>
<td>21.5</td>
</tr>
</tbody>
</table>

No significant differences in mean duration of phases 1, 2, and 3 between the force groups (ANOVA, \( p \geq 0.1 \)).

Table III. Mean rate of tooth movement (\( \mu m/day \)) and SD for the forces of 50, 100, and 200 gm during the initial phase (1), arrest of tooth movement (2), acceleration phase (3), and linear tooth movement (4)

<table>
<thead>
<tr>
<th>Force</th>
<th>Phase</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>n</th>
<th>Mean</th>
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<td>14</td>
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<td>5.5</td>
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<td>2.1</td>
<td>13.0</td>
<td>9</td>
<td>0.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15</td>
<td>23.6</td>
<td>10.8</td>
<td>13</td>
<td>23.5</td>
<td>9.4</td>
<td>13</td>
<td>22.7</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
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<td>59.3</td>
<td>14.8</td>
<td>11</td>
<td>63.8</td>
<td>19.6</td>
<td>10</td>
<td>62.7</td>
<td>22.1</td>
</tr>
</tbody>
</table>

No significant differences in mean rate of tooth movement during phases 1, 2, 3, and 4 between the force groups (ANOVA, \( p \geq 0.1 \)).

differences exist between the independent and paired samples in each phase. In the control group (0 gm), the mean amount of tooth movement over the whole experimental period was 2 \( \mu m \).

A large individual variation was found for the mean rate of tooth movement in all force groups. Differences in individual reaction are illustrated in the time-displacement curves of three experimental sides in different dogs with the same force of 100 gm (Fig. 4).

Tooth movement during phases 3 and 4 is continuous, without periods of arrest. Differences in the maximum rate of tooth movement during phase 4 between the force groups are not significant; 72, 76, and 73 \( \mu m/day \) for 50, 100, and 200 gm, respectively. No significant correlation was found between the individual mean rates of tooth movement for the different phases, except for phases 3 and 4, which were highly correlated (Pearson 0.69, \( p < 0.01 \)).

No significant differences in mesial movement of the anchorage unit were found between the three force groups (ANOVA, \( p \geq 0.05 \)). Differences in loss of anchorage as a percentage of the total amount of tooth movement between phases 1, 3, and 4 were not significant. \( (t \text{ test, } p > 0.05, \text{ Table IV}) \).

The rate of tooth movement during phases 1, 3, and 4 and also the duration of phase 2 were compared between the left and the right sides of each dog. A significant correlation between both sides was found for mean rate of tooth movement during phases 3 (\( p < 0.05 \)) and during phase 4 (\( p < 0.01 \), Table V). Time-displacement curves of the left and the right sides of each dog usually are close together, independent of the magnitude of the force (Fig. 5). In some cases, a marked similarity was found in the time-displacement curves of brother dogs (Fig. 6). Intraclass correlation coefficients for brother dogs were lower than for the left-right comparison but still significant for the rate of tooth movement during phases 1 (\( p < 0.01 \)) and 4 (0.01 \( \leq p < 0.05 \)) (Table V).

DISCUSSION

Since Reitan's experiments,\(^{1,2,4,14-16}\) it is known that the structure and density of bone has an influence on the rate of orthodontic tooth movement. Although the alveolar bone of dogs is generally denser than in human beings,\(^6\) differences between the anatomy of the periodontal ligament and alveolar bone of dogs and human beings are rather small and in this respect, beagles are generally accepted as a good model for comparison with human beings.\(^17\) In this experiment, complete healing of the alveolar bone after extraction of the third
Fig. 5. Time-displacement curves of left and right sides of two different dogs. In dog 1 forces of 100 and 200 gm were used, in dog 2 forces of 50 and 200 gm.

Fig. 6. Time-displacement curve of experimental sides of two twin brother dogs with forces of 50 and 200 gm.

Table IV. Mesial movement of the anchorage unit as a percentage (%) and SD of the total amount of tooth movement for the force groups of 50, 100, and 200 gm during phases 1, 3, and 4

<table>
<thead>
<tr>
<th>Phase</th>
<th>Force</th>
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<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean</td>
<td>SD</td>
<td>n</td>
</tr>
<tr>
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<td>4</td>
<td>13</td>
<td>21</td>
<td>21.6</td>
<td>8</td>
</tr>
</tbody>
</table>

No significant differences between the force groups (NOVA, \(p > 0.1\)) nor between the phases (\(t\) test, \(p > 0.05\)).

Table V. Pearson correlation coefficients for mean rate of tooth movement \(M\) (\(\mu m/\text{day}\)) during phases 1, 3, and 4 and for mean duration \(D\) (days) of phase 2 for the left and the right sides of each dog. Intraclass correlation coefficients for rate of tooth movement for brother dogs

<table>
<thead>
<tr>
<th>Phase</th>
<th>L-R comparison</th>
<th>n</th>
<th>Brother-brother comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 1</td>
<td>0.22</td>
<td>17</td>
<td>0.59**</td>
</tr>
<tr>
<td>D 2</td>
<td>-0.14</td>
<td>18</td>
<td>-0.42</td>
</tr>
<tr>
<td>M 3</td>
<td>0.50*</td>
<td>17</td>
<td>-0.33</td>
</tr>
<tr>
<td>M 4</td>
<td>0.92**</td>
<td>12</td>
<td>0.56*</td>
</tr>
</tbody>
</table>

*0.01 \(\leq p < 0.05\); **\(p < 0.1\).
premolar was allowed, to provide an experimental site with a uniform bone structure.

It can be concluded that tooth movement measured in this experiment indeed is the result of the applied orthodontic forces, since no significant spontaneous tooth movement was measured in the control group where no elastics were attached. This means that functional forces of tongue or cheek and biting forces do not contribute to the distal movement of the second premolar. Also, contraction of transseptal fibers that might occur after extraction of the third premolar does not produce forces large enough to result in distalization of the second premolar.

The time-displacement curves of the three force groups show a comparable pattern. Phase 1 can be interpreted as the initial movement of a tooth in its socket. Because of the orthodontic force, the width of the periodontal ligament is reduced on the pressure side. This movement is limited by hydrodynamic damping as is described earlier by Bien. A large instantaneous movement will be followed by a delayed reaction due to viscoelastic properties of the periodontal ligament. With increasing force, the initial tooth movement becomes larger.

Phase 2 can be considered as a period of arrest of tooth movement and is probably associated with hyalinization in the periodontal ligaments. Hyalinization areas appear earlier and are more extensive if higher forces are used. Although the extension of these areas might be related to force magnitude, this seems to have no clinical significance for bodily tooth movement in the present circumstances, as the duration of phase 2 was independent of the force magnitude. This may be explained by the fact that during bodily tooth movement, forces are more equally distributed along the surface of the alveolar bone than during tipping, reducing the risk of hyalinization. A large individual variation was found in the duration of phase 2, ranging from 0 to 35 days independent of the applied force. This might indicate that differences in bone density or in metabolic activities in bone or periodontal ligament play an important role.

Phase 3 is characterized by a continuous tooth movement with an increasing rate. This acceleration phase may be interpreted as a period in which biologic processes involved in remodeling of the periodontal ligament and alveolar bone reach their maximum capacity. This may also explain why, subsequently, constant tooth movement is observed in phase 4. The small differences in the maximum rate of tooth movement between the force groups seem to indicate that there is a biologic limit for the rate of bodily tooth movement in beagle dogs. Independent of force magnitude, only incidentally no change in tooth position was found between two consecutive measurements during phases 3 and 4. This means that once tooth movement has started, bone remodeling and periodontal ligament turnover takes place at a more or less constant rate.

The root surface area on the distal side of the second lower premolar in beagle dogs is estimated to be 0.5 cm². In the force groups of 50, 100 and 200 gm, this would initially result in a pressure at the root surface of about 100, 200, and 400 gm/cm², respectively. Large differences exist in the optimum pressure advised by different authors: 250 to 300 gm/cm², 210 to 250 gm/cm², 70 to 140 gm/cm², and 80 gm/cm². In our study, however, no significant differences in rate of tooth movement between initial pressures of approximately 100, 200, and 400 gm/cm² could be found. The total root surface area of the anchorage unit is estimated to be 10 times the root surface area of the lower second premolar, so initial pressure in the periodontal ligament of these teeth would be about 10, 20 and 40 gm/cm² for the three force groups. Also, in the anchorage unit, no significant differences in rate of tooth movement were found. So it seems that not only with “high” pressures, but also with “low” pressures in the periodontal ligament, the rate of tooth movement is not closely related to force magnitude. This indicates that no linear relationship exists between the initial pressure in the periodontal ligament and the rate of bodily tooth movement.

The actual movement of the second premolar is the difference between the amount of tooth movement measured intraorally and the mesial movement of the anchorage unit. Calculation of these differences, however, was not justified because of the relatively large difference in the errors between the radiographic and the intraoral measurements of 0.18 and 0.01 mm, respectively.

Large individual differences in the rate of tooth movement were found in all force groups. This is in agreement with previous studies in cats. An explanation could be that each individual animal has its own optimum pressure for tooth movement and that in the “slow movers,” the optimum forces were not applied. On the other hand, the results of the left and the right sides in each dog are highly correlated, although different forces were applied. This might suggest that those “slow movers” were unable to move faster because of lower metabolic
capacity resulting in slower bone turnover. The striking similarity of some time-displacement curves of brother dogs suggests a possible influence of genetic factors. The absence of such similarity in some other twin pairs might be explained by the fact that they were not identical twins.

CONCLUSION

It must be concluded that other factors than magnitude of force are involved in determining the rate of subsequent tooth movement. Individual differences in bone density, bone metabolism, and turnover in the periodontal ligament may be responsible for the variation. More insight into these factors might lead to the possibility of individual strategies in clinical orthodontic therapy.

REFERENCES