European Journal of Orthodontics 26 (2004) 483–490
European Journal of Orthodontics vol. 26 no. 5

The rat as a model for orthodontic tooth movement—a critical review and a proposed solution

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SUMMARY The aims of this study were to perform a systematic review of the use of rats as a model for experimental tooth movement, to give a critical evaluation of the use of elastics as a force delivery system, and to describe a newly designed well-defined model for tooth movement in rats.

The literature from 1981 to 2002 indicates that in 57 per cent of animal studies on orthodontic tooth movement, rats were used, but in many of these investigations the experimental set-up was poorly documented. Only three of the 159 studies fulfilled the inclusion criteria for a good model: a force magnitude of less than 20 cN; moving molar(s) mesially; an experimental duration longer than 2 weeks; and no extra experimental condition such as drug intervention.

As more than one-quarter of the studies on tooth movement in rats used elastics to produce an orthodontic force, and as the forces they produced and their force decay during decompression are unknown, their mechanical characteristics on decompression were tested. Elastics stored under dry conditions or in water showed significant force decay from around 45 N to almost 0 N within the first 0.2 mm of decompression.

With regard to the above-mentioned shortcomings of using rats as a model for tooth movement, a newly designed experimental appliance for tooth movement in rats was evaluated. It proved to be stable and simple and able to deliver a continuous and constant force as low as 10 cN on all three molars together during an experimental period of 12 weeks without interference in animal welfare, and was able to compensate for the effects of molar distal drift and continuous incisor eruption.

Introduction

In spite of a century of experience in the orthodontic profession of moving teeth by force application, little is known of the basic mechanism behind this process. Approaches in daily orthodontic practice are based on clinical experience rather than experimental data. Although the optimal efficiency in tooth movement is the ultimate goal in clinical orthodontics, no evidence-based force regime can be recommended (Burstone, 1989; Ren *et al.*, 2003a). For such a recommendation, greater knowledge is required on the relationship between the applied force system and tissue reactions in terms of the remodelling of bone and the periodontal ligament (PDL), and the cellular response (Reitan and Kvam, 1971; Melsen, 1999). To achieve such knowledge, well-defined standardized and reproducible force delivery systems are needed. This, together with a correct description of the morphological and biomechanical properties of the tooth and its surrounding structures, will then enable the estimation of stresses and strains in the PDL during orthodontic tooth movement by validating finite element models simulating tooth movement.

Until now a large number of experimental studies in a variety of animal species, such as rats, dogs, cats and monkeys, have been performed to obtain more insight into the biological response to orthodontic forces. These investigations, however, did not initiate major clinical innovations (Ren *et al.*, 2003a).

One of the major concerns related to animal experiments is whether findings can be extrapolated to the human situation. As the vast majority of all studies in experimental animals have been performed in rats, morphological and physiological differences between rat and human alveolar bone and PDL have to be considered. The alveolar bone of rats is generally denser than that in humans. It shows no osteons and its bone plates lack marrow spaces. The osteoid tissue along the alveolar bone surfaces is generally less abundant in rats than in humans (Reitan and Kvam, 1971). Some studies report that the extracellular matrix of rat bone contains relatively little acid mucopolysaccharides and the calcium balance of rats seems to be more controlled by intestinal absorption than by bone tissue. Classical histological studies have also revealed structural dissimilarities in the arrangement of the periodontal fibres and the supporting structures (Romanos and Bernimoulin, 1990; Romanos *et al.*, 1991). Finally, tissue development during root formation and tissue changes incident to orthodontic treatment appear to be faster in rats than in humans, although their principal mechanisms are the same (Kvam, 1967; Rygh, 1972).

Despite the differences, rats are generally considered to be a good model to study orthodontic tooth movement, which has several practical advantages. First, they are relatively inexpensive, which facilitates the use of large samples, and can be housed for a long period of time. Second, the histological preparation of rat material is easier than, for example, dog material. A third important advantage is that most antibodies required for cellular and molecular biological techniques are only available for mice and rats. Finally, transgenic strains are almost exclusively developed in small rodents. As mice are too small to place an effective orthodontic appliance, it is obvious that rats are the first choice in this field.

An investigation of the recent literature on experimental tooth movement in rats revealed that many of these studies show severe shortcomings, which are partly related to the physiology of the animals and partly to the design of the orthodontic appliance (Ren *et al.*, 2003a).

Little attention has been paid to physiological aspects, such as the natural distal drift of molars or the continuous eruption of incisors. Distal drift may lead to an underestimation of the experimental mesial molar movement, and continuous incisor eruption may lead to a poor definition of anchorage and a deficient control of force direction, which in many cases hampers interpretation of the data.

The design of experimental orthodontic appliances also often shows severe shortcomings. As the effect of an applied force on the tissues is related to the size of the tooth involved, the magnitude of the applied force should be related to its root surface area (Isaacson *et al.*, 1993). Rat teeth are very tiny (a rat molar is approximately 50 times smaller than a human molar), which complicates the design of an efficient orthodontic appliance that is suited to produce a constant and continuous force with an acceptable force range.

Both clinical and animal studies have shown that there are several phases in tooth movement (Proffit and Fields, 2000). It takes from a few days to a few weeks to reach the so-called 'linear phase', where real tooth movement through bone occurs. Therefore, studies aimed at describing the characteristics and biological response in the linear phase of tooth movement should have an experimental period of at least 2 weeks. Furthermore, as interrupted force application and changing the force magnitude hamper the interpretation of the relationship between force and tooth displacement, constant and continuous forces are recommended for experimental research (Van Leeuwen *et al.*, 1999).

In many experimental tooth movement studies, non-standardized or ill-defined springs or elastics have been chosen as the force delivery system, although their force magnitude is largely uncontrolled and unknown. Especially, the definition of 'elastics' is not clear. In most cases, the word elastics probably refers to elastomeric ligatures that are commonly used in orthodontic practice to ligate a wire into a bracket (Taloumis *et al.*, 1997). These elastomeric ligatures are made of polyurethanes, the exact composition of which is unknown. Polyurethane is a generic term given to complex polymers that contain urethane linkages.

The elastic properties of polyurethanes are dependent on their composition, and most do not show ideal elastic characteristics, as their elasticity is time and environment dependent. The effect of time, temperature, salivary pH, and water absorption on the force loss, permanent deformation and strength of elastomeric products such as bands, chains, and ligatures has been reported in the literature (Baty *et al.*, 1994; Nattrass *et al.*, 1998; Eliades *et al.*, 1999). One common feature in these experiments was that the material properties were derived from tests under stretching conditions, according to its application in a clinical setting. However, when elastics are inserted between rat molars to generate forces for experimental tooth movement, the force delivery is not caused by stretching but by decompression. Unfortunately, the force decay rate, the amount of force decay and dimensional changes of elastomeric ligatures during decompression have not yet been adequately investigated.

In summary, although rats are the most often used animal for studying tooth movement, general shortcomings seem to exist in the experimental set-up of studies on rats from the literature. Thus, the aim of this investigation was to perform a systematic review of the use of rats as a model for experimental tooth movement, to give a critical evaluation of the use of elastics in this type of research, and finally to propose a well-defined experimental model for tooth movement in rats.

Materials and methods

Literature on experimental tooth movement in animals

The Medline database was used to search the publications in English from 1981 to 2002 using the following search strategy:

1 explode 'Orthodontics'/all SUBHEADINGS in MIME, MJME
2 (tooth movement) or (tooth displacement)
3 1 and 2
4 (rat or rats) and 3
5 (dog or dogs) and 3
6 (primate or primates) and 3
7 (cat or cats) and 3
8 (mouse or mice) and 3
9 (rabbit or rabbits) and 3
10 (guinea pig* or swine or ferret* or hamster* or gerbil*) and 3

An analysis was performed on the results from No. 4 based on the following exclusion/inclusion criteria. Exclusion criteria: studies were excluded when none of the following information concerning tooth movement was mentioned in the text—force magnitude, duration of the experiment, direction of movement. The remaining studies were then evaluated and listed by force magnitude, experimental teeth, direction of tooth movement and duration of the experiment. As a last step, the final inclusion criteria were applied as follows: (1) force magnitude less than or equal to 20 cN, (2) moving molar(s) mesially, (3) duration longer than or equal to 2 weeks, (4) no drug intervention.

Testing of elastics

'Silver' elastomeric ligatures (Sani-ties, GAC International, New York, USA) were tested. Two groups of 10 elastics were used. One group was stored under dry conditions and the other group in water for 3 weeks before testing. The original thickness of the elastics was 0.8 mm, the inside diameter 1.6 mm, and the outside diameter 3.0 mm. A universal testing machine (Instron model 1011, Instron Corp. Canton, Massachusetts, USA) was used to test the force magnitude and the thickness of the elastics during decompression. The decompression rate of the elastics was set as 0.50 mm/minute. The measurement error of the load cell was 1 per cent. An elastic was stretched by stringing it to two pieces of dental floss which were pulled apart. Subsequently, it was inserted between the loading cell and the stile. The stile was semi-cylindric with a diameter of 3.00 mm. The distance between the loading cell and the stile was set at 0.1 mm. The dental floss was then removed before testing. Reading of the force magnitude was recorded at every 0.05 mm of decompression. Student's *t*-tests were performed to compare the mean force magnitudes between dry elastics and those stored in water at each decompression point.

Rat model

Thirty young male Wistar rats (aged 6 weeks, body weight 150–250 g) were used for the experiment. The animals were acclimatized for at least 1 week before the experiment started. The animals were housed under normal laboratory conditions and they were fed powdered laboratory rat chow (Sniff, Soest, The Netherlands) and water *ad libitum*. A standard 12 hour light–dark cycle was maintained. Ethical permission for the study was obtained according to the guidelines for animal experiments of the University of Nijmegen.

A split-mouth design was used, with the experimental side randomly chosen and the contralateral as the control. For each experimental side an orthodontic appliance was made. Stainless steel ligature wires with a diameter of 0.2 mm (Dentaurum, Pforzheim, Germany) were bent to enclose all three maxillary molars as one unit, using a dry rat skull as a model. To this ligature wire a Sentalloy® closed coil spring (10 cN, wire diameter 0.22 mm, eyelet diameter 0.56 mm, GAC, New York, USA) was attached. A schematic drawing of the appliance system is shown in Figure 1.

The super-elastic properties of the springs and the delivered force were tested in a laboratory set-up at 38°C. The springs proved to deliver a reproducible force of 10 ± 2 cN over a range of 3–15 mm activation (Ren *et al.*, 2003b).

Before the orthodontic appliance was placed, general anaesthesia was induced with an intraperitoneal injection of FFM-mix containing fentanyl citrate 0.079 mg/ml, fluanisone 2.5 mg/ml (Janssen Animal Health, Beerse, Belgium) and midazolam 2.5 mg/ml (Roche, Mijdrecht, The Netherlands) at a dose of 2.7 ml/kg body weight. Oxygen was supplied during surgery to facilitate breathing, which may become temporarily difficult due to bleeding inside the nasal cavity. A transverse hole was drilled through the alveolar bone and both maxillary incisors at the mid-root level using a drilling bur (D0205, Dentsply, Montigny le Bretonneux, France). Cooling was performed with a syringe and physiological saline. A stainless steel ligature wire (diameter 0.3 mm, Dentaurum) was inserted through the hole.

The pre-formed orthodontic appliance was bonded on to the experimental maxillary molar unit with light-curing bonding material (Clearfil SE Bond, Kuraray Europe GmbH, Düsseldorf, Germany). Bonding was applied until the buccal and palatal wires were completely embedded in the bonding material, then it was light cured. The Sentalloy® spring was kept free of the bonding material at the mesial side of the pre-formed

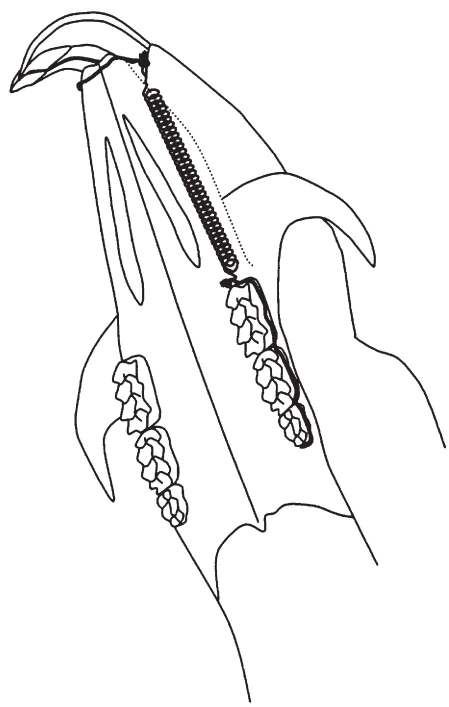

Figure 1 A schematic drawing of the proposed rat model.

ligature. It was activated and subsequently attached to the ligature wire through the snout and the incisors.

Measurements with a digital calliper (Mitutoyo Co., Kawasaki, Japan) were performed at 0, 1, 2, 3, 4, 8 and 12 weeks under general inhalation anaesthesia (isofluorane and N_2O; Abbott BV, Hoofddorp, The Netherlands). The distance between the most mesial point of the maxillary molar unit and the enamel–cementum border of the ipsilateral maxillary incisor at the gingival level was measured (I–M distance) at the experimental and the control side. The appliance was checked twice weekly, and more bonding material was added when necessary.

After the intra-oral measurements, the animal was placed in a specially designed rat cephaloshat for standardized radiography. A triangular wooden wedge was placed under the mandible to ensure a horizontal position. The position of the mandible was adapted in the horizontal plane until the pin stick of the cephaloshat pointed to the midline of the nose. A tube connected to the isofluorane supply was placed with a funnel-shaped open end over the snout of the rat. In this way the animal was kept sedated during the radiographic procedure. Kodak dental film (size 4) was used; the exposure time was set as 0.6 seconds based on pilot results (unreported); the film focus distance was 1.0 m. The time needed for all of the above procedures was approximately 20–30 minutes.

Five rats were sacrificed at 1, 2, 4, and 8 weeks, and the remaining ones at 12 weeks. The amount of tooth movement at the experimental and control sides was compared across time by ANOVA. The mean rate of experimental tooth movement from 0 to 3 weeks was compared with that from 4 to 12 weeks by a paired *t*-test.

Results

Literature search

The results of the literature search are given in Table 1.

Table 1 The results of the literature search.

Searching key words	Number of publications
1 explode 'Orthodontics'/all SUBHEADINGS in MIME, MJME	11 604
2 (tooth movement) or (tooth displacement)	2654
3 1 and 2	2512
4 (rat or rats) and 3	175
5 (dog or dogs) and 3	52
6 (primate or primates) and 3	31
7 (cat or cats) and 3	23
8 (mouse or mice) and 3	15
9 (rabbit or rabbits) and 3	12
10 (guinea pig* or swine or ferret* or hamster* or gerbil*) and 3	12

One hundred and seventy-five studies on tooth movement were performed in rats, which comprised 55 per cent of the 320 animal investigations. Rats and dogs, as the most often used experimental animals, together comprised 71 per cent of the studies; primates were used in 10 per cent, cats in 7 per cent, mice in 5 per cent, and rabbits in 4 per cent. Other animals were used less often.

After applying the exclusion criteria on all publications on tooth movement in rats, 153 publications remained. Figure 2a shows the distribution of the force magnitudes

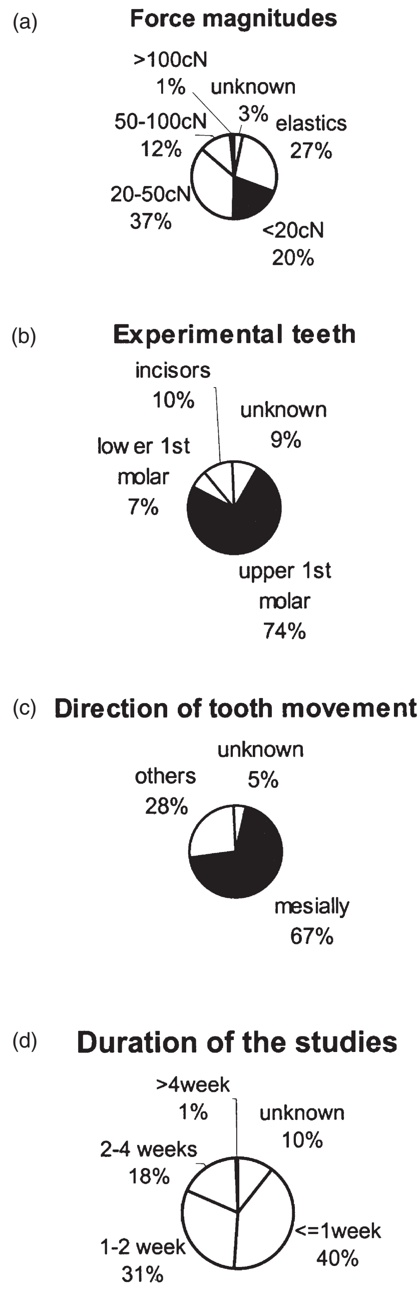

Figure 2 The characteristics of the designs used in experimental studies on orthodontic tooth movement in rats, as retrieved from the literature. (a) Force magnitude, (b) experimental tooth, (c) direction of movement, (d) duration.

used in the above-mentioned 153 studies: 20 per cent used force magnitudes less than 20 cN, 37 per cent forces of 20–50 cN, and 12 per cent forces as high as 50–100 cN. In 27 per cent elastics which produced forces of unknown magnitude were used.

Figure 2b shows that 74 per cent of the rat studies used upper first molars as the experimental teeth; 7 per cent the lower first molar, and 10 per cent incisors. In 67 per cent of the studies the molars were moved in a mesial direction (Figure 2c). According to Figure 2d, 40 per cent of the experiments had a duration of less than 1 week, 31 per cent of 1–2 weeks, and 18 per cent of 2–4 weeks.

Only the following three studies met all of the inclusion criteria (force magnitude less than or equal to 20cN; moving molar(s) mesially; duration longer than or equal to 2 weeks; no drug intervention):

King *et al.* (1991): forces of 20, 40 and 60 cN;
Keeling *et al.* (1993): forces of 20, 40 and 60 cN;
Nixon *et al.* (1993) forces of 20, 40 and 60 cN.

Force decay of elastics

Figure 3 shows the decompression–force magnitude curve of dry and wet elastics. The initial force magnitudes as exerted at a stile–loading cell distance of 0.10 mm differed significantly between elastics stored in dry and wet conditions (42.3 ± 2.98 N and 46.5 ± 3.06 N, respectively, $P < 0.05$). There was no general difference between dry and wet elastics in terms of force decay. In both situations, the high initial forces sharply decreased to 15 N (decompression of the elastics to 0.15 mm), 5 N (decompression to 0.20 mm), then to almost 0 N (decompression to 0.30 mm).

Rat model

The rats had normal weight gain during the experimental period. Of the 30 experimental animals, one rat died during surgery, probably due to bleeding in the snout. This bleeding may have blocked the normal breathing of the animal leading to suffocation. One animal was excluded from the experiment at week 5 because of obvious signs of stress, and one at week 3 because of appliance loss. The remaining animals were healthy throughout the experiment.

Figure 4 shows that the change in I–M distance at the experimental sides was significantly larger than at the control sides for each measuring point ($P < 0.001$). The I–M distance at the control sides remained almost unchanged. The I–M distance at the experimental sides decreased over time, and the rate of decrease slowed after 3 weeks. Experimental tooth movement of the molar unit, which is the tooth movement produced by orthodontic force over time, is the difference in I–M distance between the experimental and control sides. It showed that the velocity of the experimental tooth movement was higher in the initial phase (0–3 weeks) than in the later phase (4–12 weeks) ($P < 0.01$). A series of standardized X-ray photographs at 0, 1, 2, 3, 4, 8 and 12 weeks are shown in Figure 5. These demonstrate that continuous eruption of the upper incisors was efficiently prevented, and that the direction of the force exerted by the coil spring was maintained at the level of the occlusal plane throughout the experimental period.

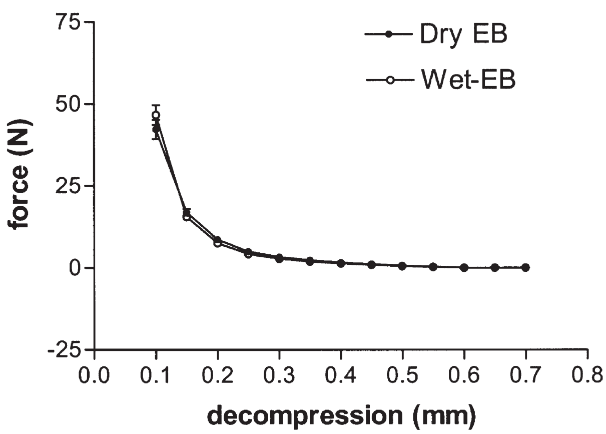

Figure 3 Tooth movement in young rats. Open circles indicate the mean decrease in incisor–molar (I–M) distance at the experimental sides (± standard deviation), solid triangles the mean decrease in I–M distance at the control sides (± standard deviation). Solid circles are the subtraction of the decrease in I–M distance at the control sides from the experimental sides (± standard deviation), which is the experimental tooth movement.

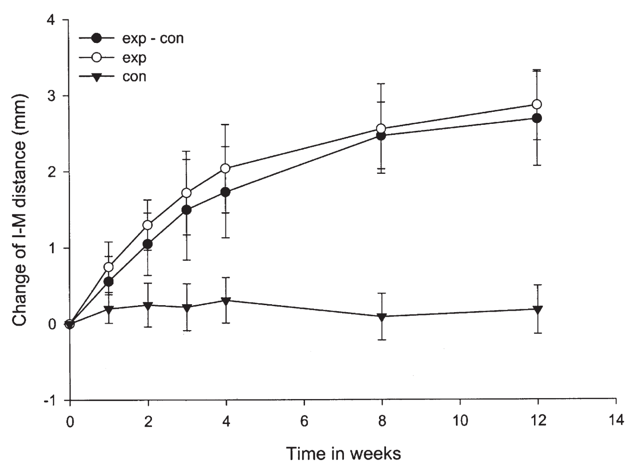

Figure 4 The force decay curve of elastics. Solid circles relate to data from elastics stored in dry conditions, open circles from elastics stored in wet conditions.

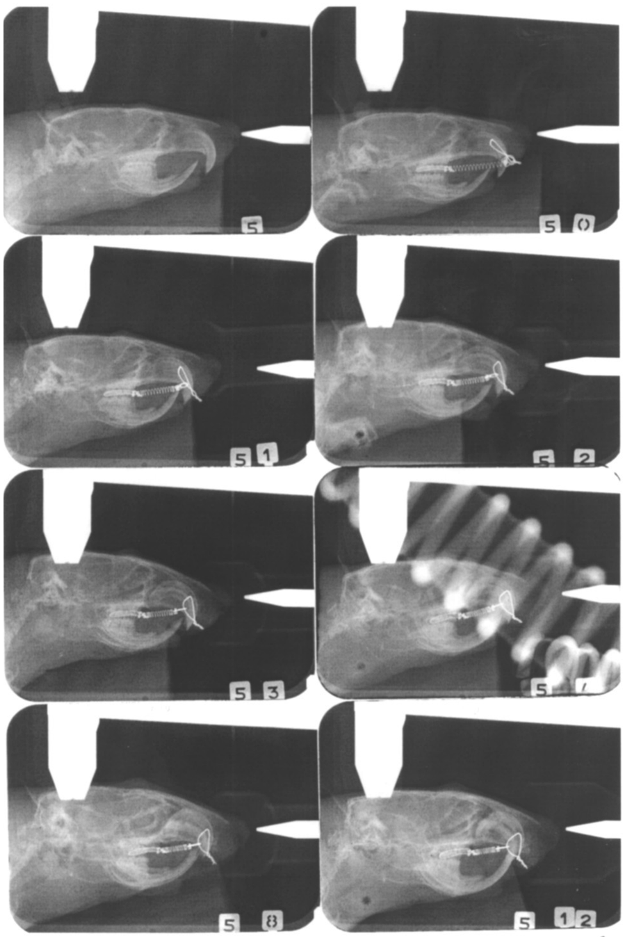

Figure 5 A series of standardized radiographs at 0, 1, 2, 3, 4, 8 and 12 weeks, respectively. The first picture on the left is just prior to surgery.

Discussion

In the majority of the animal experimental studies on orthodontic tooth movement found in the literature, force was not measured at all or only measured at the start of the experiment, no matter how long the experimental period. It is doubtful whether this uncontrolled experimental situation can produce reliable and interpretable data on the relationship between force and tooth movement. To compare humans and rats, an estimation of root surface areas may give an indication of the force magnitude to be used. A human molar is approximately 50 times larger than a rat molar, which means that the effect of a 20 cN force on a rat molar is comparable with a force of 1000 cN (= 1 kg) on a human molar. It is surprising to note that 80 per cent of the reported studies used forces over 20 cN or forces of unknown magnitudes on rats and in only 20 per cent of the studies forces of 20 cN or less were applied (Figure 2a).

In more than one-quarter (27.5 per cent) of the publications, elastics were used to produce an orthodontic force in rats. The force delivered by elastics has never been adequately described. Besides 'elastic bands' as the most often used term, other terms such as 'elastic module', 'orthodontic elastics', 'elastic rubber' and 'separating elastics' are widely used. Measurements on their initial forces or their force decay have never been published.

The use of elastics to separate rat molars is often referred to as Waldo's method (Waldo and Rothblatt, 1954). However, while the rubber bands were described as an orthodontic intermaxillary elastic no. 5, no details were provided about its composition, dimensions, or mechanical properties. The major drawback of that publication is that, although a theoretical analysis of force distribution on teeth and surrounding tissues, and some histological micrographs have been given, no data are presented on the force decay of the elastics. Until now no attempt has been made to judge the scientific merits of Waldo's method. For a correct interpretation of the result of the measurements on the mechanical properties of the elastics in the present study, the dimensions of the rat dentition have to be taken into consideration. The intermolar supragingival space between a rat's maxillary first and second molars can be estimated as 0.12 mm. Thus, the initial force delivered by the elastics after insertion was as high as 45 N (Figure 4). If this is translated to the human situation, it should be compared with a force of 225 kg. Studies in dogs have shown that the initial displacement within the first minute is limited to approximately 0.02 mm (Van Driel *et al.*, 2000). If it is assumed that the mechanical characteristic of the PDL of a dog and rat are similar, it can be reasoned that in the very initial stage, the elastics are probably decompressed to approximately 0.16 mm. This would mean a decrease in force from 45 N to approximately 15 N. The normal width of the PDL of a rat molar is approximately 0.12–0.15 mm (Tengku *et al.*, 2000). This means that when the PDL at the mesial side of the first molar and the distal side of the second molar are maximally compressed, the distance between the molars occupied by the elastic might range from 0.36 to 0.42 mm. However, this maximal compression of the PDL is only possible theoretically. Dog studies have shown that the initial compression of the PDL stabilizes after approximately 5 hours after a total movement of approximately 0.06 mm (Van Driel *et al.*, 2000). When applying these data to a rat model, the decompression of elastics at this stage leaves a space of approximately 0.24 mm between the molars, which produces about 5 N force. It is obvious that the PDL of the first and second molars is severely loaded in the first few hours after placement of an elastic band to separate these teeth. Morphological investigations in rats and mice have already revealed that tissue damage and remodelling start within a few hours (Brudvik and Rygh, 1993a, b).

In other rat studies (Bridges *et al.*, 1988; Gibson *et al.*, 1992; Gu *et al.*, 1999), a variety of coil springs have been used. The composition of these springs is mostly unknown, and the initial force magnitude has been given more often according to the manufacturer's specification than to test results. Furthermore, in the majority of the studies, no attempt has been made to measure force decay during the experimental period.

To compare tooth movement in humans and rats, mesial molar movement is favourable. The molars should be used because rat incisors have a completely different morphology, and mesial movement is indicated because the buccal side has a very limited amount of bone which is also more compact than at the mesial side. The design of most rat studies meets this preference.

When using the inclusion criteria mentioned previously, only three studies fulfilled all criteria (King *et al.*, 1991; Keeling *et al.*, 1993; Nixon *et al.*, 1993). These studies are actually from the same research group and their data were most probably retrieved from the same animal experiment or at least based on the same animal model. However, the rat model used is not recommendable (for a detailed description of this model see King *et al.*, 1991). First, only the initial force was controlled, and there was no reactivation. They used 20 cN as the lowest force, but also forces of 40 and 60 cN, which are rather high. Second, they reported that the success rate for the appliance in the surviving animals was 79 per cent and that the animals showed a tendency to lose weight during the experiment (King *et al.*, 1991). In order to eliminate extraneous forces from occlusion and tissue impingement from the appliance, the mandibular first and second molars were extracted. All the above-mentioned points indicate poor animal welfare. The longest experimental period in these studies was just 2 weeks. It is doubtful whether this model is still applicable if the experimental period is, for example, 12 weeks, as in the new model. Third, continuous eruption of incisors was not taken into account in the appliance design, although distal drift of the maxillary molars was calculated.

In the new rat model, a split-mouth design was chosen because of the confounding effects of the physiological distal drift of the molars, the physiological growth of the snout and the concomitant forward movement of the incisors, the continuous eruption of the incisors and the possible distal tipping of the incisors used as anchorage. Compensation for these effects was achieved by calculating the differences between the I–M distances at the experimental and control sides. The changes in these differences were used as a measure of actual experimental tooth movement caused by the orthodontic appliance (Ren *et al.*, 2003b). X-ray photographs showed that the appliance stayed in position, tooth movement was apparent from the radiographs, and continuous eruption of the upper incisors was effectively prevented. Abrasion of the maxillary incisors was compensated by overeruption of the mandibular incisors. The direction of force by the coil spring was kept at the level of the occlusal plane over 12 weeks. As the springs proved to deliver a constant and continuous force of around 10 cN over a range of 3–15 mm activation, there was no need for reactivation during the experimental period and as the force of 10 cN was distributed over all three molars, the effect could be estimated to be the same as a force of 170 cN (10/3 cN $\times$ 50) on a human molar. This is a considerable improvement compared with the use of 20 cN on one rat molar, as reported in the literature, as the effect of such a force is comparable with a force of 1000 cN on a human molar, which is far too high. As the effect of occlusal interdigitation on experimental tooth movement is not definite, the new model did not take this factor into consideration. The I–M distance at the control sides remained almost unchanged throughout the experiment. This is the combined result from the decrease in I–M distance due to tipping of the incisors, the increase in I–M distance due to forward growth of the snout, and distal drift of the molars. Although the force magnitude was the same over time, tooth movement slowed after 3 weeks. This might be explained by the regional morphological differences in alveolar bone. From experiments (Reitan and Kvam, 1971), it is known that the local structure of the alveolar bone (i.e. bone density) has an influence on the rate of tooth movement. Regional differences in bone morphology have been indicated in the rat mandible: the alveolar bone mesial of the first molar becomes more compact in the mesial direction. The same morphological characteristics may also hold true for the maxilla, which means in the course of mesial tooth movement, resistance in bone was not constant but increased, and consequently the rate of tooth movement would be expected to slow down.

Conclusion

Although rats were generally thought to be a good model for the study of orthodontic tooth movement, there are a number of severe shortcomings in the experimental designs reported in the literature. The use of elastics is not indicated to provide a controlled force delivering system for experimental tooth movement studies in rats. The newly designed appliance proved to be stable and simple and able to deliver a continuous and constant force as low as 10 cN on all three molars together during an experimental period of 12 weeks without interference in animal welfare, and is able to compensate for the effects of molar distal drift and continuous incisor eruption.

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Acknowledgements

The authors wish to thank Dr J. Wolke, Department of Experimental Periodontology and Biomaterials for his kind help in testing the elastics. The custom-made Sentalloy springs were kindly provided by GAC (Lomberg BV, Soest, The Netherlands).

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