Optimum Force Magnitude for Orthodontic Tooth Movement: A Systematic Literature Review

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Abstract: The aim of this study was to perform a meta-analysis of the literature concerning the optimal force or range of forces for orthodontic tooth movement. Over 400 articles both on human research and animal experiments were found in Medline and by hand searching of main orthodontic and dental journals. Articles on animal experiments were in the majority. A wide range of animal species such as rat, cat, rabbit, beagle dog, monkey, mouse, and guinea pig were used. Besides variation in species, there was also a wide range of force magnitudes, teeth under study, directions of tooth movement, duration of experimental period, and force reactivation. Furthermore, hardly any experiments were reported that provide information on the relation between the velocity of tooth movement and the magnitude of the applied force. Data from human research on the efficiency of orthodontic tooth movement appeared to be very limited. The large variation in data from current literature made it impossible to perform a meta-analysis. Therefore, we have systematically reviewed the literature. It appeared that no evidence about the optimal force level in orthodontics could be extracted from literature. Well-controlled clinical studies and more standardized animal experiments in the orthodontic field are required to provide more insight into the relation between the applied force and the rate of tooth movement. (*Angle Orthod* 2003;73:86–92.)

Key Words: Orthodontics; Optimum force; Force magnitude; Velocity; Tooth movement; Stress; Strain; Meta-analysis; Systematic review

INTRODUCTION

In literature, different opinions can be found about the force level that results in optimal mechanical conditions within the periodontal ligament for orthodontic tooth movement. It is assumed that an optimal force system is important for an adequate biological response in the periodontal ligament.¹ It also has been suggested for a long time that the optimal force is related to the surface area of the root.^{2–4}

In the past 70 years, the concept of optimal force has changed considerably. Schwarz⁵ proposed the classic con-

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Revised and Accepted: July 2002. Submitted: February 2002. © 2003 by The EH Angle Education and Research Foundation, Inc. cept of the optimal force. He defined optimal continuous force as "the force leading to a change in tissue pressure that approximated the capillary vessels' blood pressure, thus preventing their occlusion in the compressed periodontal ligament." According to Schwarz⁵, forces well below the optimal level cause no reaction in the periodontal ligament. Forces exceeding the optimal level would lead to areas of tissue necrosis, preventing frontal bone resorption. Tooth movement would thus be delayed until undermining resorption had eliminated the necrotic tissue obstacle.

Schwarz's⁵ definition was slightly modified by Oppenheim,⁶ who advocated the use of the lightest force capable of bringing about tooth movement, and by Reitan,⁷ who demonstrated cell-free compressed areas within the pressure site even in cases where light forces were applied and also advocated the use of very light forces.

The current concept of optimal force is based on the hypothesis that a force of a certain magnitude and temporal characteristics (continuous vs intermittent, constant vs declining, etc) would be capable of producing a maximum rate of tooth movement without tissue damage and with maximum patient comfort. The optimal force for tooth movement may differ for each tooth and for each individual patient.⁸

The magnitude of force has received significant attention

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in orthodontics without considering that it is important only because it is related to other characteristics of the force system and surface area of the periodontal ligament over which it is dissipated. The forces, which are applied to the crowns of the teeth, are distributed over the entire supporting structure and so are the stresses and strains. From a cellular point of view, distribution of stress (force per unit area), distortion of the periodontal ligament (shear stress, strain), and bone deformation (strain) are critical factors, and the remodeling response is directly related to stress and strain levels within the periodontium.9,10 The orthodontic force as an extrinsic mechanical stimulus thus evokes a biologic cellular response that aims to restore equilibrium by remodeling of the periodontal supporting tissues.^{11–13} Because it is very difficult to measure stresses and strains within the periodontal ligament of loaded teeth directly, only measuring the forces that are applied directly to teeth with known root surface areas can provide an estimate of these parameters.

A thorough systematic review of the available literature on this topic could be a basis for the application of appropriate forces in clinical orthodontics. But such a review on this topic has never been published. Nowadays, a metaanalysis of the literature, ie, a mathematical analysis of summary results across a group of studies with common underlying characteristics, appears to be the preferred choice. In contrast to traditional narrative literature reviews, a meta-analysis allows covering a large number of studies. It focuses on the size of treatment effect, not just whether results are statistically significant.

Therefore, the present study was planned as a meta-analysis aiming at a description of the relation between orthodontic force and the rate of subsequent tooth movement and, more specifically, at the assessment of an optimal force or force range for clinical use in orthodontics.

MATERIALS AND METHODS

Search strategy for identification of studies

Medline was searched from the year 1966 until December 2001 using the following search strategy.

- 1. 14483—(orthodont* in ti) or (orthodont* in ab).
- 2. 4637—(tooth or teeth) near movement.
- 3. 104315-force*.
- 4. 536—#1 and #2 and #3.
- 5. 476—#4 not case-report in tg.
- 6. 305—#5 and human in tg.
- 7. 161—#5 and animal in tg.

Publications before 1966 and the most recent ones were hand-searched in main dental and orthodontic journals. The reference lists of selected articles were searched, and references to related articles were followed up. The sources retrieved by queries 6 and 7 and by hand-search were manually evaluated by two independent researchers (Dr Ren and Dr Maltha) using the following exclusion criteria.

- 1. No quantification of orthodontic force magnitude (eg, use of separation elastics).
- 2. No quantification of rate or amount of tooth movement.
- 3. No control group or split-mouth design.
- 4. Number of experimental sites per group ≤ 5 .
- 5. Use of extraoral or functional appliances.
- 6. Observation period ≤ 1 week.
- 7. Medication and surgical or physical intervention other than orthodontics in experimental design.

Data extraction

From each study that remained after application of the exclusion criteria, the data were extracted as follows.

- 1. Title description.
- 2. Number of experimental conditions.
- 3. Number of individuals or sites per experimental condition.
- 4. Age or weight of the experimental subjects.
- 5. Method for measuring tooth movement.
- 6. Method for measuring force.
- 7. System of force control.
- 8. Frequency of reactivation of appliance (if applicable).
- 9. Type of appliance.
- 10. Initial force magnitude in cN.
- 11. Direction of force.
- 12. Type of tooth movement.
- 13. Duration of experimental period in weeks.
- 14. Mean rate of tooth movement over experimental period in mm/wk.

RESULTS

After applying the exclusion criteria, 17 of 161 articles on animal studies and 12 of 305 articles on human studies remained. The general results of these studies are summarized in Tables 1 through 3.

The main properties of articles included in this analysis are as follows: The articles on animal experiments (Tables 1 and 2) show a wide range of species such as cat (n = 2), beagle dog (n = 5), monkey (n = 2), rat (n = 7), rabbit (n = 1), and guinea pig (n = 2).

In the two studies on cat maxillary canines, tipping forces ranging from 40 to 500 cN were used.^{14,15} The five studies in dogs used bodily movement of mandibular second premolars (M. Von Böhl et al and J. C. Maltha et al, personal communication).^{16–18} The forces used in these studies ranged from 10 to 1200 cN. One of the studies gave detailed information on tooth movement only for some of the experimental animals; the other four have a rather uniform experimental setup. One of the studies on monkeys is on maxillary premolar movement using tipping forces of 10–

TABLE 1. List of Included Animal Studies (Cat, Dog, Monkey)

Author	Year	Ref	С	Species	B/T	Teeth	Force (cN)	D	Results
Utley	1968	14	4	Cat	Т	Cmax	40–60 135–165 400–560	4w	No relation between rate of cuspid TM and force magnitude
Mitchell	1973	15	2	Cat	Т	Cmax	150	12–25w	Higher force per unit of root surface area in- creases rate of TM
Fortin	1971	16	2	Dog	В	P_2 mand	150–200 450	4w	Light forces result in greater TM than heavier forces
Pilon	1996	17	3	Dog	В	P ₂ mand	50 100 200	17w	No relationship between force magnitude and TM
Leeuwen	1999	18	2	Dog	В	P_2 mand	10 25	17w	Force regimen has more influence on rate of TM than force magnitude
Von Böhl	2001	p.c.	2	Dog	В	P_2 mand	25	17w	Large individual variations in velocity of TM
Maltha	2001	p.c.	2	Dog	В	P₂mand	300 10 300 600 1200	17w	Large individual variations in velocity of TM; in some individuals no effect of increasing force
Dellinger	1967	19	4	Monkey	Т	P₁max	10 50 100 300	8w	Optimal force for intrusion is 50 cN
Steiner	1981	20	2	Monkey	В	Imax, Imand	50	16w	The central incisors were moved labially 0.19 mm/wk on average

Ref indicates number of the study in the reference list; C, number of experimental conditions in the referred study; B/T, Bodily or tipping tooth movement; Teeth: I, incisor; C, canine; P, premolar; M, molar; Max, maxillary; mand, mandible; L, left; R, right; _{1,2} number of the teeth; D, duration of longest observation in the study; TM, tooth movement; p.c., personal communication.

TABLE 2. List of Included Anima	I Studies (Rat, Rabbit, Guine	a Pig)*
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Author	Year	Ref	С	Species	B/T	Teeth	Force (cN)	D	Results
Storey	1955	21	9	Rat, rabbit, and guinea pig	Т	Imax	25 50 150	1w	Increase in rate of TM with increasing force in rabbit and rat, not in guinea pig
Steigman	1981	22	4	Rat	I	Imand	2–10 14–23 38–40	2w	Medium loads are optimal for intrusive movement
Bridges	1988	23	2	Rat	Т	M₁max	60	2w	Young rats TM about 0.66 mm/wk, adult rats TM about 0.45 mm/wk (linear stage)
King	1991	29	6	Rat	Т	M₁max	20 40 60	2w	20 cN group TM about 0.28/wk, 40 cN group TM about 0.16 mm/wk, 60 cN group TM about 0.17 mm/wk (linear stage)
Gibson	1992	30	2	Rat	Т	M₁max	40	2w	TM about 0.16 mm/wk (linear stage)
King	1994	31	2	Rat	Т	M₁max	40	2w	Young rats TM about 0.27 mm/wk, adult rats TM about 0.25 mm/wk (linear stage)
Gu	1999	32	2	Rat	Т	M₁max	40	2w	TM 0.18 mm/wk
Botting	1973	33	2	Guinea pig	Т	Imax	3–7 30–40	2w	Optimal range of force in growing guinea pig between 3–7 g and 30–40 g ap- plied to the upper incisor teeth

* For an explanation of the abbreviations see Table 1.

300 cN;¹⁹ the other study is on incisors, using a bodily force of 50 cN.²⁰ From the seven studies on rats, five studied the effect of forces ranging from 20 to 60 cN on the maxillary first molar.^{21–26} The other two studies dealt with the max-

illary and mandibular incisors, respectively, using forces from 10 to 150 cN.^{21,22} Six of these seven studies on rats used tipping forces, and one study used an intrusive force. Only one study on rabbits was included in which tipping

Author	Year	Ref	С	B/T	Teeth	Force (cN)	D	Results
Storey and Smith	1952	2	2	В	Cmand	175–300 400–600	9w	Optimum force range for maximum rate of movement is 150–200 cN for canines
Lee	1964	34	2	B/T	Cmax	450	>1w	Optimum force level between 150 and 260 cN
Andreasen	1967	35	2	Т	Mmax	200 400	12w	Higher force yielded 2.5 times tooth displace- ment of the lower force
Hixon	1969	36	2	Т	Cmax	300 0–1500	8w	Higher forces per unit root area increase the rate of TM
Hixon	1972	37	2	Т	Cmax	300 0–1000	6w	Higher forces produce more rapid movement than lighter ones
Boester	1972	3	4	Т	Cmax	55 140 225 300	10w	55 cN force yielded less TM than 140, 225, and 300 cN, whereas latter three forces pro- duced the same amount of TM
Anderasen	1980	38	4	Т	LM RM LC RC	100–150 400–500 100–150 400–500	10w	In general greater forces produced greater rate of tooth movement
Lee	1995	39	2	B/T	Cmax	35–450	7w	Maximum rates of TM is 0.78–1.34 mm/wk for tipping movement with force average 337– 388 cN, and 0.86–1.37 mm/wk for bodily movement with force average 354–375 cN
Owman-Moll	1996a	40	2	т	Pmax	50 100	4–7w	No difference in TM in 50 cN group and 100 cN group
Owman-Moll	1996b	41	2	Т	Pmax	50 200	7w	TM increased 50% with 200 cN as compared to 50 cN
Lundgren	1996	42	2	т	Pmax	50	7w	Horizontal movement of the tooth crown was 0.8 mm during the first week and 3.7 mm af- ter 7w
Iwasaki	2000	43	2	В	Cmax	18 60	12w	18 cN could produce effective TM

TABLE 3. List of Included Studies on Humans*

* For an explanation of the abbreviations see Table 1.

forces of 25–150 cN were used on maxillary incisors.²¹ The two studies on guinea pigs were both on maxillary incisors, using tipping forces from 10 to 150 cN.^{21,28} These large variations in species, applied force, experimental setup, and type of tooth movement made it impossible to perform the review as a meta-analysis of the relation between force magnitude and rate of tooth movement on the basis of animal experiments.

The number of human studies included in this review (n = 12) dealing with the relation between force magnitude and rate of tooth movement is rather limited (Table 3). Eight studies dealt with canine retraction.^{2,3,29–34} A wide range of initial forces (18–1500 cN) were used in these studies; also, the regimen of reactivation and other parameters, such as the type of movement, showed a wide variation. Three articles reported on premolar tipping using forces from 50 to 200 cN,^{35–37} and two articles reported on molar tipping using forces from 100 to 500 cN.^{32,38} The number and the homogeneity of the included human studies were too limited to enable a meta-analysis.

DISCUSSION

Interest in characterizing the nature of the relation between the magnitudes of applied force and the rate of or-

thodontic tooth movement and the extent of anchorage loss began in the 1950s. The use of "light" forces once became popular on the basis of the classic studies of Storey and Smith² and Reitan⁷ in the 1950s and 1960s, respectively. The assumption was that a so-called differential movement of teeth, at first proposed by Begg,¹³ could be generally achieved. Moreover, it was generally thought that light forces are more efficient and more "biologic" and, hence, less painful. Although the "light force concept" sounds attractive, the term is used freely and arbitrarily. There is neither universal consensus nor sound scientific evidence regarding specific numeric values of force magnitude. The concept of light force is application-dependent: a force that is considered too high for a certain application may be ideal for another,8 but few studies ever gave substantial evidence for this concept.

In the last two decades, a growing interest became manifest for the view that orthodontic tooth movement should be considered as the result of biological reactions to externally applied mechanical stimuli. One of the central questions raised was whether higher stresses and strains result in greater biologic activity and thus in a faster rate of tooth movement or whether an optimal force or force range would exist to stimulate this process. This question led to the classic article of Quinn and Yoshikawa⁴ in which they proposed four possible models for the relation between force magnitude and the rate of orthodontic tooth movement.

Searching the orthodontic literature revealed that no publications are available that elucidate the fundamental clinical question about the optimal force. On evaluating all the retrieved literature, two periods can be distinguished. Earlier studies (1950-1980) dealt more with the efficiency of orthodontic tooth movement than do later studies. Great efforts were taken to investigate the optimal force that could produce a maximum rate of tooth movement and the advantages of light forces compared with heavy forces. The differential force theory as proposed by Begg¹³ was also a topic of interest. All these studies, however, did not lead to a general conclusion. In later years (1981–2001), the studies mainly focused on topics as histological or cell biological changes, or changes in blood flow velocity during different stages of tooth movement, and on the side effects of orthodontic treatment such as root resorption and drug effects on tooth movement. Only few studies further investigated the efficiency of orthodontic tooth movement; also, these studies did not lead to a general conclusion.

We aimed at performing a meta-analysis of the existing literature. This, however, appeared to be impossible. Four main problems were encountered throughout the literature.

The first difficulty is the inability to precisely calculate the distribution of stresses and strains at the level of the periodontal ligament. Most literature pertaining to the relation between the magnitudes of applied force and rate of tooth movement is based on measurements of the magnitude of the applied force and the rate of tooth movement. But the forces applied to the teeth per se are not the critical factors leading to the biologic reactions. The fundamental considerations are the local stresses and strains that are experienced by the cells within the supporting tissues.^{11,12,15} Direct measurement of these parameters is almost impossible, and current literature could not provide a reliable biomechanical model from which they can be derived.

The second problem is that many of the experiments cited failed to control the type of tooth movement. In most experiments, tipping tooth movement has been performed, which means that an uneven distribution of stresses and strains is invoked within the periodontal ligament. The clinical result is that the crown and root of a tooth move at different rates or even in different directions. The center of rotation, which determines the rate of crown and root movement, is difficult to determine and very likely to change during the tipping movement.¹⁶ Therefore, a welldefined and reproducible tipping tooth movement is almost impossible. A related problem is that measurements of tooth displacement generally are performed at the crowns rather than at the center of resistance, leading to an overestimation of the effect of the applied force. Therefore, experimental studies with tipping movement are difficult to interpret, and their results are very hard to compare with other experiments.

The third consideration that contributes to confusion on the relationship between force and rate of tooth movement is that orthodontic tooth movement can be divided into several phases that were categorized by Burstone¹⁷ as initial phase, lag phase, and postlag phase. Later studies on beagle dogs proposed four phases: initial phase, phase of arrest, phase of start, and linear phase.¹⁸ Structural changes in bony and periodontal tissues during the different phases of tooth movement lead to changes in their biomechanical characteristics and thus to changes in local stresses and strains within the periodontium and to modulations in the biological response. In many studies, tooth movement was evaluated over a relatively short period of time, leading to data pertaining only to the first two phases of the process and not to the postlag or linear phase in which true orthodontic tooth movement is considered to take place.

Finally, a large interindividual variation is recognized in both human research and animal experiments. Even with standardized, constant, and equal forces, the rate of orthodontic tooth movement may vary substantially among and even within individuals (M. Von Böhl et al and J. C. Maltha et al, personal communication).^{17–19} On the other hand, with substantially different forces, rates of tooth movement may be almost the same among or within individuals.^{18,20,21} These individual differences in tooth movement characteristics are possibly related to individual variation in the structure of and cellular activity within the periodontal ligament and alveolar bone²² or to localized differences in the expression of factors such as cytokines and growth factors.²³

After more than half a century of research on orthodontic tooth movement, it is disappointing to conclude that the answer to the question of the optimal force is still far away. The four main problems outlined above largely explain why the current confusion exists. So a rationale for future work should take these problems into consideration. But the stress/strain distribution in the periodontal ligament, PDL, is a point of major concern. No empirical or experimental evidence has ever been reported to verify the concept of tooth translation. This concept assumes a homogeneous distribution of stress/strain in the PDL. Because the center of rotation is in continuous repositioning in vivo, the biomechanical concept of translation can only exist instantaneously and cannot be sustained over time by any existing appliance system. Clinical tooth movement is accompanied by a constantly changing spectrum of stress/strain in the PDL that ranges from compression to tension.24

As a starting point to estimate the optimal force, mathematical modeling could be performed by evaluating all individual data on tooth movement that can be retrieved from literature. A nonlinear regression analysis of these data may provide an equation to describe the characteristics of the relation between force magnitude and the rate of tooth movement. In this way, the power of the analysis is increased because small sample size and a large interindividual variation is a general shortcoming in almost every single study. Care should be taken in categorizing data according to different force systems, ie, tipping vs bodily tooth movement and continuous vs intermittent application of force. Such a model may identify a range of optimal force and the maximal velocity of tooth movement produced.

Because experimental or clinical techniques are usually limited in applying known complex force systems, biomechanical modeling has become a necessity. From a biomechanical point of view, stress and/or strain in the periodontal ligament play an important role in tooth movement. The finite element method (FEM) is a useful technique for stress analysis in biological systems, where local stress and/ or strain cannot be measured directly in a nondestructive manner. As such, it offers a possibility for accurate modeling of the tooth-periodontium system with its complicated 3-dimensional geometry. Different material models, ie, a viscoelastic material model or a poroelastic model, have been proposed for analyzing the mechanical properties of the PDL.²⁵⁻²⁸ Such models must be validated by biological data from well-controlled experimental or clinical studies that go beyond the early phases of orthodontic tooth movement, thus providing data on linear phases as well. Ultimately, a computer stimulation model might be constructed to reflect the local tissues' reactions in terms of stress and strain and to predict tooth movement in relation to orthodontic forces.

CONCLUSIONS

Because it is not possible to perform a meta-analysis of the relation between force magnitude and rate of tooth movement from current literature, no evidence-based force level could be recommended for the optimal efficiency in clinical orthodontics. But promising alternative approaches are suggested as mathematical modeling on retrieved data from literature, biomechanical modeling by FEM for stress/ strain analysis, and well-controlled clinical studies or animal experiments with standardized setup. These combined efforts might lead to a better understanding ofhow the efficiency of orthodontic treatment can be improved in the future.

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