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THE FORCE REQUIREMENTS FOR TOOTH MOVEMENT PART I: TIPPING AND BODILY MOVEMENT

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Specific data on the relation between force and tooth movement is essential not only to facilitate non-traumatic orthodontic treatment but also to establish a sound basis for appliance design. Whilst the broad approaches to orthodontic tooth movement appear to be the application of tipping and/or bodily movement, no scientific comparison between these two types of movement has yet been made. This article describes experiments which repeat investigations of Storey and Smith into the relation between the force applied and the rate of tipping movement and their extension to include bodily movement. Twenty adolescent male patients requiring distal movement of upper cuspid teeth as a part of orthodontic treatment were each fitted with calibrated cuspid retraction springs. The appliances were designed to induce bodily movement on one side of the mouth concurrently with tipping movement on the other. Initial force applications were identical, and the experiments lasted for up to eleven weeks following one activation of the retraction springs. The results of these experiments were compared with those of other workers, and an explanation of the causes of the past controversy regarding various theories of tooth movement is offered.

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Introduction

In previous studies of tooth movement[1,2] that investigated the relation between the rate of movement and the force exerted by orthodontic springs, teeth were moved by a tipping action without bracket engagement. Orthodontic treatment often requires bodily movement, but, as yet, the forces required to achieve specific rates of this type of movement have not been studied. Consequently, the following experiments were designed to investigate the rate of tooth movement and the force required to move teeth by both a tipping motion and a bodily motion, concurrently, in the same patient. In all cases the upper cuspid teeth were moved distally: one bodily and the other tipped. In this way, results obtained for tipping movement without bracket engagement to the archwire could be compared not only with the results of bodily movement in the same experiment but also with the tipping movement results previously reported by Storey and Smith[1] and Smith and Storey.[2]

Early researchers of tooth movement - Sandsdedt[3] in 1904, and Oppenheim[4] in 1911 - described tissue changes which occurred in the teeth and surrounding tissues of laboratory animals when subjected to force. Schwartz[5] in 1932 was the first to measure force application using calibrated springs. He was also the first to suggest that "pressure", not "force", was the critical factor in determining tissue changes during tooth movement. Schwarz's[5] findings confirmed those of Sandstedt's[3] and, in addition, demonstrated that differing degrees of force produced different tissue changes. However, the forces applied in Schwarz's experiments during the whole course of tooth movement were not enumerated accurately because the springs were reactivated during the experiments. Although Schwarz called these forces "pressures", he considered neither the root area nor the distribution of stress along the tooth root.

In 1935 Oppenheim[6] reported a new series of experiments on man; in these he called attention to the differences noted in human tissues compared with those seen in the monkey. In a later report,[7] in 1944, he discussed an appliance that would not induce pathological change in teeth and surrounding tissues. Although he did not record force magnitude, he did record amounts of tooth movement. He concluded that all forces induced pathological change and, therefore, as repair occurred after the cessation of force, intermittent force application was best.

In 1938, Stuteville[8-10] in a series of experiments on dog and man concluded that a biologically safe movement could probably be obtained with light continuous forces. Oppenheim,[7] compared the effects of "light" intermittent and constant forces. He reaffirmed his earlier conclusions; but, added that forces should be "light" without defining what this meant. Reitan[16-22] measured

Rates of movement of various types but did not give force values

accurately. He demonstrated that bone, periodontal membrane and cementum all react in different ways to different stresses and that tissue changes occur faster in proliferating tissues.

In the second half of the twentieth century, researchers began taking more accurate measurements of force and the rate of tooth movement. The new investigations directly relating force to the rate of tooth movement in the human subject were initiated by Storey and Smith[1], who, in 1952, measured the rate of tipping movement of cuspid teeth subjected to "light" and "heavy" forces. They used springs of known load-deflection characteristics to move cuspid teeth in one arch and measured movement against a fixed point in the opposing arch after the patients closed into centric occlusion. They found that the rate of movement varied with the force applied and that, as the force was reduced and the tooth started to move, the rate of movement was slow. With further reduction in force, the rate of movement increased to a maximum; and with still further reduction, decreased until movement ceased. Thus, the optimum range of forces first suggested by Schwarz[5] in his experiments on dogs was demonstrated. At the conclusion of this work, Storey and Smith[1] suggested that "pressure", not "force", was the important factor in producing tooth movement. For cuspid teeth, Smith and Storey[2] and Storey and Smith[1] found that maximum rates of tipping movement occurred in the 160-270 gf (1.6-2.7 N) range.

In 1953, Storey[18] carried out a radiographic study of the bone changes which occurred during orthodontic tooth movement. He took intra-oral radiographs of teeth moved by a known force and demonstrated radiographically the formation of the new lamina dura. The centre of rotation of the experimental teeth was inferred to be located in the region of the apical third of the tooth root. He confirmed Sandstedt's[3] histological findings that, with heavy forces, tooth movement would occur by a process of undermining resorption. This was demonstrated both radiographically and by measurements of the rates of tooth movement. Storey[18] also showed different bone responses to light and heavy forces, the most significant difference being that heavy forces produced a slower rate of bone change than lighter forces. He concluded that the periodontal membrane and bone were normally in a state of continual removal and replacement; and that, with light forces, dense laminated bone forms in tension areas and ahead of the area of resorption on the pressure side. He also concluded, however, that with heavy forces, laminated bone forms only after the completion of movement or when the force is decreased. The radiographic method he used made it possible to evaluate the extent of this variation in bone and the influence of such factors as age, health and sex. His study[19] also demonstrated that greater amounts of tooth movement occur in the female during the latter half of the menstrual cycle.

In 1957, Reitan[13] published results of his experiments which related total amounts of tooth movement in the human and the dog. The forces used were not listed in all cases, and details of his technique for measuring actual tooth movement were not clear. But insofar as it was possible to estimate the forces being exerted at any particular time and the actual amount of tooth movement, his results appear to cofirm the work of Storey and Smith[1]. He concluded from his study that higher stresses could occur in tissue around a tooth being tipped than around one being moved bodily.

In 1960, Burstone and Groves[20] carried out a study designed primarily to demonstrate the lowest possible force values that would retract the anterior teeth by simple tipping if relatively continuous force were appplied. They also investigated the relation between force magnitude and the rate of tooth movement and recorded the initial forces and rates of release. No threshold values for anterior tooth movement were found. Optimal rates of tooth movement were observed in the 50 to 75 gf (0.5 - 0.75 N) range. Increasing the magnitude of the force did not increase the rate of tooth movement.

In 1962, Burstone[21] pointed out the importance of rate-of-movement studies as opposed to total movement studies. Using a "relatively constant" force of 125 gf (1.25N), he demonstrated three phases of tooth movement which he called the "Initial " phase, the "Lag" phase and the "Post-lag" phase.

Since the work of Storey and Smith[1] and Smith and Storey[2], several other researchers[22-26] have conducted tooth movement experiments. Andreasen[26] and Hixon[24,25] caused controversy by criticizing both Storey's "optimal force" theory and Begg's "differential force" theory. In 1981, Quinn[27] summarised six published experiments[1,23-26] and drew attention to the diversity of the experimental methods: he pointed out, for example, that the measuring techniques and time intervals between measurements differed, that quantities were expressed in incorrect units and that results were interpreted in different ways. Hence, it is not suprising that there is still inconclusive and controversial debate on the question of optimal force, anchorage and differential force.

The following study, with the variables of age, sex and the amount of initial force application controlled, was planned to repeat Storey and Smith's study of tipping movement and to compare the tipping movement results of both studies with concurrent bodily movement.

Experimental Method

Twenty male patients in good health and aged between twelve and fourteen years were selected for orthodontic treatment. These patients required distal movement of the maxillary cuspid teeth as part of routine orthodontic treatment. The orthodontic appliance used was similar to that used by Storey and Smith[1] with the following modifications:

i The experimental teeth were all maxillary teeth.

ii The final rectangular arches were: 0.018" x 0.022" (0.46mm x 0.56mm).

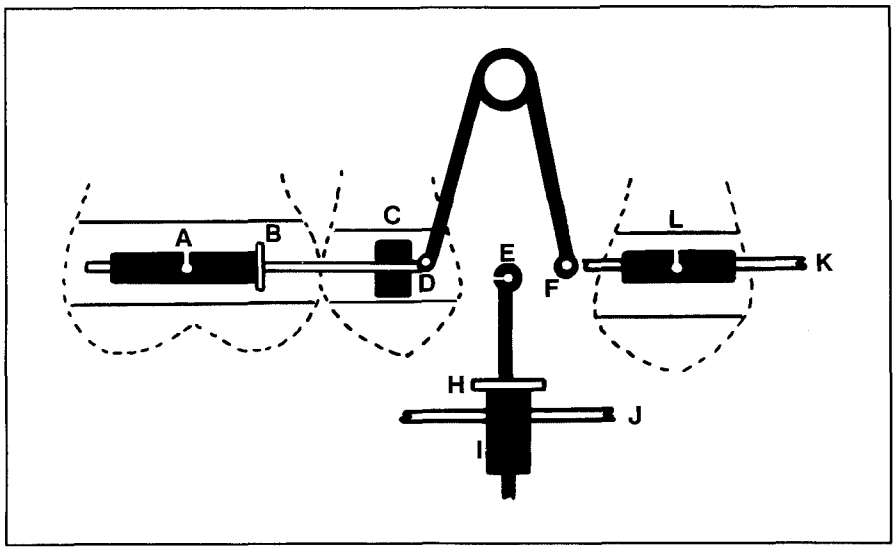


Figure 1. Diagrammatic representation of the appliance used for the measurement of the amount of bodily movement.

A Reference point on buccal tube on first molar
B Stop on arch wire
C Bracket on second bicuspid band
D Measuring point on fixed arm of spring
E Reference point on end of detachable arm
F Measuring point on free arm of spring
G Bracket with measuring point on cuspid tooth
H Stop on detachable arm
I Buccal tube soldered to upper .022" x .028" arch wire
J Lower arch wire
K Anterior segment of arch wire
L Measuring point on buccal tube on cuspid tooth

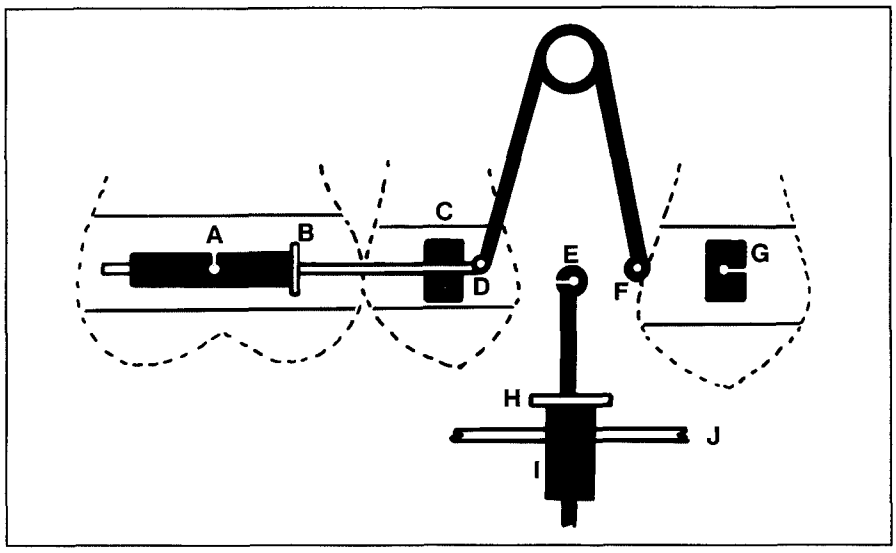


Figure 2. Diagrammatic representation of the appliance used for the measurement of the amount of tipping movement.

A Reference point on buccal tube on first molar
B Stop on arch wire
C Bracket on second bicuspid band
D Measuring point on fixed arm of spring
E Reference point on end of detachable arm
F Measuring point on free arm of spring
G Bracket with measuring point on cuspid tooth
H Stop on detachable arm
I Buccal tube soldered to upper .022" x .028" arch wire
J Lower arch wire

iii The force and tooth movement distances were measured with dividers placed in measuring holes drilled into the fixed and free arms of the springs; and into the buccal tubes and brackets placed on the molar and cuspid teeth respectively. These measurements were transferred to a micro-divider setter (an instrument with two holes to take the points of the dividers at any distance up to 100mm and which gives readings using a radial vernier in divisions of 0.025mm). The accuracy of the instruments was tested at the Australian Commonwealth Bureau of Dental Standards and found to coincide within +/- 0.13mm when three dimensions were measured five times. The transfer of measurements was also tested and found to be accuate to the same degree. Each required measurement was taken as many times as necessary so that three measurements fell within 0.13mm; these three measurements were recorded. The patient opened and closed into centric occlusion between measurements.

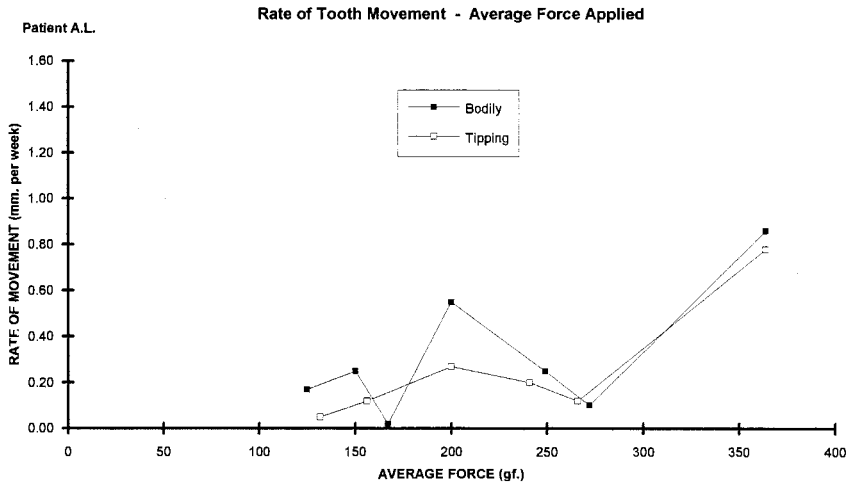
Weekly force values were obtained by reference to the load-deflection curves for the particular springs used on each patient. The distance between the measuring points on the cuspid and anchor teeth was taken to be equal to the deflection of the spring at any particular time. Direct measurements of the actual spring deflection were regarded as unreliable because the free end of the spring arm moved during the measuring process. By contrast, the measuring points on the cuspid and molar teeth, being fixed, were taken to be more accurate indicators of the amounts of tooth movement and, therefore, spring deflection. Results of experiments in which the total amounts of tooth movement did not match the load-deflection curves of the springs were discarded. Thus, fourteen experimental tooth movements were analysed from a final sample of nine patients.

iv To ascertain the tooth positions at rest, the first measurements were taken prior to the application of force.

v A horizontally placed buccal tube was attached to the band around the relevant cuspid tooth to ensure bodily movement.

All patients were fully banded to ensure stability of the dental arches throughout the experiment. The springs used for the experiment were made from 0.024"(0.61mm) diameter, stainless steel heat-treated wire wound around a 0.125"(3.18mm) mandrel. The arms of the twenty-two springs used on

Table I. Fig. 3.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT A.L.			
		BODILY MOVEMENT			
0	450				
7	278	364	0.86	0.00	0.86
14	265	272	0.10	0.00	0.96
21	232	249	0.25	0.00	1.21
28	168	200	0.55	0.00	1.76
35	165	167	0.02	0.00	1.78
42	135	150	0.25	0.12	2.15
49	115	125	0.17	0.00	2.32
			2.20	**0.12**	
		TIPPING MOVEMENT			
0	45				
7	278	364	0.78	0.00	0.78
14	253	266	0.12	0.00	0.90
21	228	241	0.20	0.00	1.10
28	173	200	0.27	0.05	1.42
35	140	156	0.12	0.07	1.61
42	123	132	0.05	0.10	1.76
49			0.00	0.00	
			1.54	**0.22**	

the eleven patients who kept regular appointments and whose data was recorded in this study, varied in length from 8mm to 16mm because of different anatomical configurations of muscle attachments, gingival tissues and the teeth involved. These springs were soldered to lengths of 0.018" x 0.022" (0.46mm x 0.56mm) rectangular archwire.

Figures 1 and 2 show the arrangement of the measuring points and springs used in the experiment. In order to avoid rotation of the teeth during their distal movement, the free ends of the springs were attached to eyelets soldered to the centre of the distal surfaces of the cuspid bands.

Readings were taken weekly. Two cuspid tooth movements were observed for three weeks, two for five weeks, three for six weeks and seven for seven weeks. The amount of tooth movement during any one week was related to the average of the loads exerted at the start and at the end of the week. Springs were activated to an initial force of 450 gf (4.5 N), and, in none of the cases was re-activation of the springs made in any of the experimental tooth movements. Hence, the greatest force exerted was the initial force. Rates of tipping and bodily movement of cuspid teeth and anchor units were measured and related to the average force values for loads exerted in any particular week. Amounts of canine and anchor tooth movement (distances L-E and A-E respectively for bodily movement and G-E and A-E for tipping movement) were measured against the fixed point (E) in the lower arch after the patient had closed into centric occlusion. Bodily movement was confirmed radiographically. Results are shown in Table I, and, graphically, in Figures 3-11.

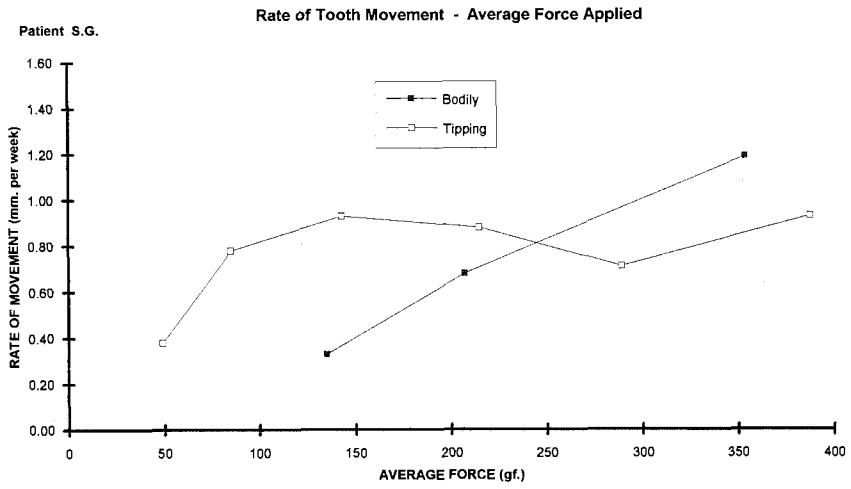
Results

The movement of fourteen cuspid teeth was studied. Twelve showed a similar pattern of movement; however, a complete range of measurements could not be undertaken in two cases (L.J. tipping and S.G. bodily) because of premature space closure.

In general, tooth movement was bi-phasic, although in some cases of bodily movement there was evidence of a third phase. The first phase commenced with a rapid movement which quickly lost its velocity so that movement became very slow and in some cases ceased. In the second phase, which followed immediately on the first, the velocity of movement rose at a fairly steady rate and reached a maximum value which, in a number of cases, closely approximated the original value in Phase 1. The rate then decreased fairly steadily until the termination of the experiment, when movement had slowed and, in some cases, ceased. Of the cases in which the bi-phasic tooth movement occurred, maximum rates of movement in the first phase occurred between 0.78mm and 1.34mm for tipping movement and between 0.86mm and 1.37mm for bodily movement; at average force ranges of between 337gf (3.37 N) and 388gf (3.88 N) and between 354gf (3.54 N) and 375gf (3.75 N) respectively. As the load fell, the rate of tooth movement decreased. At this stage, the range of forces exerted for tipping movement was from 201gf (2.01 N) to 306gf (3.06 N) and for bodily movement from 135gf (1.35 N) to 292gf (2.92 N). With further reduction in force, the rate of tooth movement again reached a high

Note: The unit of force recorded in the experiments is gf. This is because of the calibration of the instruments used at the time and also for the purpose of comparison with earlier work. To convert gf to N multiply by 0.0098.

Table I (ii). Fig. 4.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT S.G.			
		BODILY MOVEMENT			
0	45				
9	258	354	1.19	0.53	1.72
15	155	207	0.68	0.10	2.50
23	115	135	0.33	0.10	2.93
			2.20	**0.73**	**2.93**
		TIPPING MOVEMENT			
0	450				
9	273	361	1.32	0.00	1.32
15	258	265	0.10	0.00	1.42
23	240	249	0.22	0.00	1.64
30	165	202	0.76	0.05	2.47
37	128	146	0.35	0.17	2.99
44	82	105	0.38	0.07	3.44
			3.13	**0.29**	

level. The rates of movement at this high level in Phase 2 ranged between 0.27mm and 2.31mm for tipping movement and between 0.45mm and 1.01mm for bodily movement. When these high rates in Phase 2 occurred the range of forces was from 109gf (1.09 N) to 231gf (2.31N) for tipping movement and from 97gf (0.97 N) to 224gf (2.24 N) for bodily movement. With further reduction of force, the rate of tooth movement decreased. The range of forces exerted for tipping movement cases at the cessation of tooth movement was 27gf (0.27 N) to 132gf (1.32 N); for bodily movement, from 35gf (0.35 N) to 116gf (1.16 N).

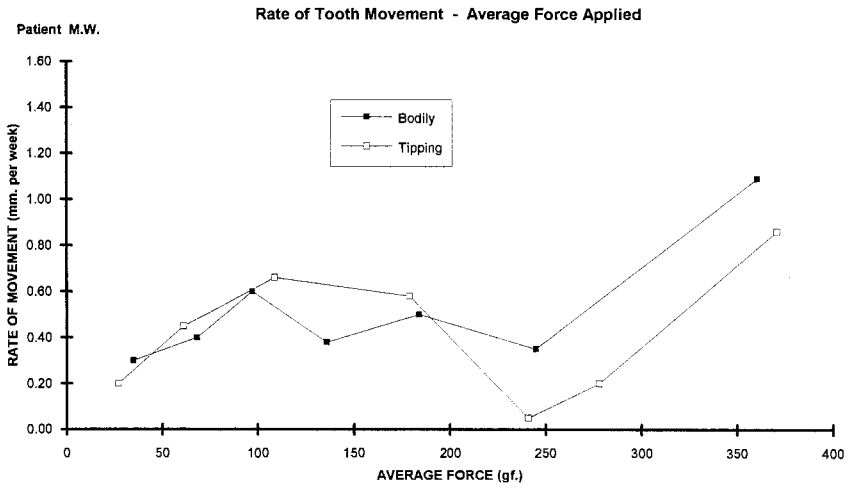
All except two cuspid teeth (L.J. tipping and S.G. bodily) moved in a similar pattern. In these two cases, tooth movement ceased because of space closure before the experiment was completed. Consequently, their curves were incomplete but followed the general tooth movement pattern up to that point. For both types of movement, in general, total amounts of movement were inversely proportional to the rates of release of the springs used. Table III shows the ranking of rates of release and amounts of tooth movement for seven cases of tipping movement and seven cases of bodily movement.

In the fourteen cases in which anchor movement was measured, most movement occurred in the high force ranges in 11 cases and in the low force range in two cases; only one case showed no anchor movement at all. The results are shown in Table I and Figures 3-11. Table II shows the relation between average force and average rate of movement for the entire group of patients. The averages of the weekly amounts of seven bodily and seven tipping movements for the first seven weeks are shown graphically in Figure 12.

Discussion

The typical pattern of tooth movement demonstrated in these experiments suggested that the high rate of movement in Phase 1 was movement through the periodontal space. This conclusion was reinforced by the fact that, in one case, half the movement in the first week occurred in the first hour; and in another case, one quarter of the total tooth movement over a seven-week period, occurred in the first two days. Further, the average of the high rates of movement in Phase 1 for both tipping and bodily movement were almost identical. The decrease in rates of tooth movement immediatly following the high rates in Phase 1 could be explained in several ways: the higher density of alveolar bone caused resistance to tooth movement; or, perhaps, de-vitalization of soft and hard tissues in areas of maximum stress induced the low rate of movement and thus prevented tooth movement until an area of necrotic tissue was removed by undermining resorption processes; or it could have been that this period, when compared with the relatively short time required for cancellous bone to be resorbed once the tooth moved, represented the relatively long time required for the compact bone of the lamina dura to be resorbed. Most of the low rates in Phase 1 were lower in tipping than in bodily movement. This is not unexpected because in tipping movement, higher stresses were probably exerted at the alveolar crest and in the apical region than were exerted in bodily movement. For the same reasons, optimal stress levels were reached sooner (in the third week) in bodily movement because in tipping movement, bone at these locations must be resorbed before stress can be distributed more evenly along the root and optimal levels of stress reached. During both types of tooth movement there was a steady reduction of force which caused a reduction in the degree of stress between root and bone. However, in tipping movement the

Table I (iii). Fig. 5.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT M.W.			
		BODILY MOVEMENT			
0	450				
7	273	361	1.09	0.12	1.21
14	218	245	0.35	0.12	1.68
21	150	184	0.50	0.10	2.28
28	123	136	0.38	0.00	2.66
35	72	97	0.60	0.00	3.26
42	45	68	0.40	0.00	3.66
49	25	35	0.30	0.00	3.96
			3.62	**0.34**	**3.96**
		TIPPING MOVEMENT			
0	450				
7	293	371	0.86	0.00	0.86
14	263	278	0.20	0.10	1.16
21	220	241	0.05	0.30	1.51
28	142	179	0.58	0.00	2.09
35	75	109	0.66	0.00	2.73
42	47	61	0.45	0.00	3.20
49	8	27	0.20	0.00	3.40
			3.00	**0.40**	**3.40**

area of contact between root and bone increased as movement proceeded. This increased area of contact resulted in a more rapid reduction of force per unit area, that is, the pressure exerted between tooth root and bone. This had been shown radiographically by Storey[23].

The average rates of movement for seven weeks were related to the average forces applied (Fig.12), and it was seen that the curves for tipping and bodily movement were mostly coincident except that optimal rates for tipping movement were greater and occurred at lower force levels.

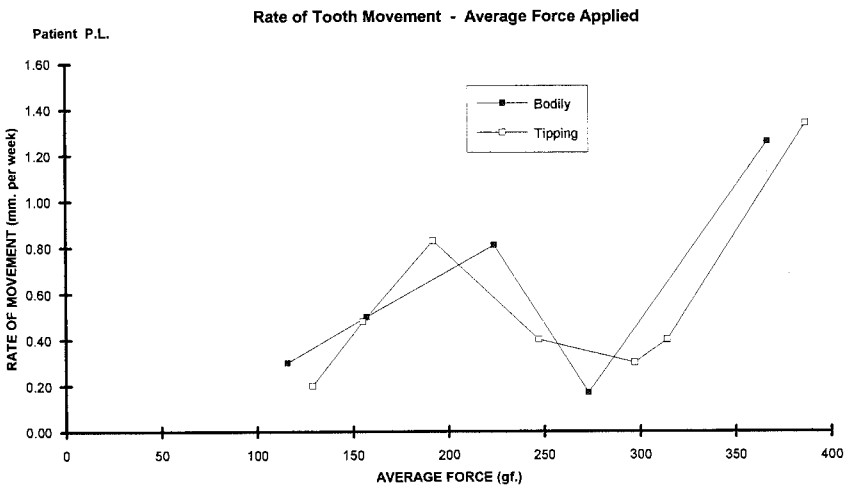
There is no theoretical reason why maximum rates of bodily movement should occur at higher force levels than maximum rates of tipping movement because, all other things being equal, if the stresses were the same, the rates of bone resorption would be the same irrespective of the type of tooth movement. However, in tipping movement, especially if the centre of rotation is within the confines of the root, a large variation in stress occurs along the "leading" and "trailing" surfaces of the root. As long as there is no excessive stress to cause undermining resorption, there should be no impediment to the rapid and safe movement of the tooth.

On average, low rates of movement in Phase 2 occurred at lower force levels for tipping than for bodily movement. This suggested that lower forces were required to initiate tipping movement than to initiate bodily movement. This is consistent with clinical experience, possibly because more bone must be resorbed in a bodily movement than in a tipping movement to achieve the same amount of crown movement along the occlusal plane; thus, more work (that is, force x distance) is required. In tipping movement, the tooth tips about a centre of rotation located within the confines of the root whereas, in bodily movement, the centre of rotation is located at infinity. If specific amounts of work are required to achieve specific amounts of direct bone resorption, less force must be required to tip a tooth than to move it bodily for the same distance. However, as teeth which have been tipped usually have to be uprighted later; it is in this uprighting stage of treatment that the amounts of work are equalized and in some cases probably exceeded, especially if excessive stress causing undermining resorption is allowed to occur.

One factor uncontrolled but measured in this study was the rate of release of the springs used. When total amounts of tooth movement, including the movement in the first week, were ranked alongside the rankings of the rates of release of the springs used for the tipping and bodily movement experiments, all except two of the seven coincided. Thus low rates of release induce greater amounts of tooth movement. This is confirmed by clinical experience using Nickel-Titanium wires which have the lowest rates of release of any material currently in use. An indication of this phenomenon is the reduction in treatment times currently being observed by the author who is using this material.

Comparisons of these results with those of other workers have shown that the results of Storey and Smith[1] and Smith and Storey[2] for optimal rates of movement generally fell within the range of rates of movement seen in this experiment; except in two cases of Storey's and Smith's which were 35 gf (0.35 N) higher in the "light" force experiment and up to 102 gf (1.02 N) higher in the "heavy" force experiment.

Table I (iv). Fig. 6.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT P.L.			
		BODILY MOVEMENT			
0	450				
7	285	367	1.26	0.12	1.38
14	262	273	0.17	0.02	1.57
21	187	224	0.81	0.12	2.50
28	127	157	0.50	0.20	3.20
35	105	116	0.30	0.12	3.62
			3.04	**0.58**	**3.62**
		TIPPING MOVEMENT			
0	450				
7	325	387	1.34	0.00	1.54
14	303	314	0.40	0.07	1.81
21	285	297	0.30	0.00	2.11
28	210	247	0.40	0.38	2.89
35	175	192	0.83	0.00	3.72
42	135	155	0.48	0.00	4.20
49	122	129	0.20	0.00	4.40
			3.95	**0.45**	**4.40**

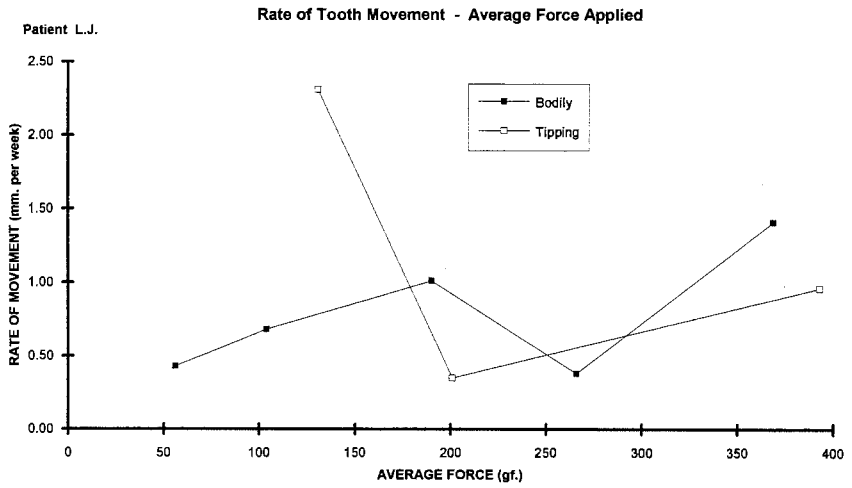
Of the sixteen tooth movements Storey and Smith studied, eleven had springs reactivated during the experiment, and seven of them demonstrated the highest rates of movement immediately after reactivation. In this, the author's, experiment there were no reactivations, and the average optimal force for tipping movements was 200 gf (2.00 N), producing an average optimal rate of 0.66mm per week. In Storey and Smith's[1] and Smith and Storey's[2] "light" force experiments, the average force was 209 gf (2.09 N), producing an average rate of optimal movement of 1.22mm per week. The higher average rate of movement in their[2] experiments may be attributed to the springs they used, which had lower rates of release than those in the author's series; also, reactivation of the springs was seen to have induced bone resorption on the tension side[18] and was associated with increased rates of movement. Storey and Smith's "heavy" force experiments demonstrated higher average optimal rates of movement than those observed in the author's experiments. They observed force ranges at optimal rates of 180-342 gf (1.8 - 3.42 N) producing an average optimal rate of 1.25 mm per week in a range of 1.0-1.75 mm per week. Of the five cases in which there was no reactivation, the average optimum forces were 196 gf (1.96 N), producing an average optimum rate of movement of 1.20 mm per week. As in this series of experiments, Storey and Smith found total amounts of movement in the majority of cases to be inversely proportional to the rates of release of the springs. Storey and Smith's[1] experiments demonstrated no rapid rates in Phase 1 because they did not take their first measurement until after the force had been applied for some time whereas, the author, in his investigation, took all his initial measurements immediately before activation.

A comparison of the results of this investigation with those of Burstone 21 reveals similarities in initial rates of tooth movement (approximately 0.35 mm per day) and the timing of the high and low rates of movement in both Phases 1 and 2. Burstone did not state whether his tooth movement experiments were for tipping or for bodily movement; however, he did point out that he hoped to develop a working hypothesis to explain and relate bony changes to stress levels in the periodontal membrane. In discussing the low rates of movement in Phase 2, he pointed out that, theoretically, if a very low stress level is introduced into the periodontal membrane, no bony transformation occurs; and furthermore, if this stress level is increased, a point is reached where bone resorption can begin - that is, a threshold stress level. He quoted experiments of Groves which showed that forces of 10 gf (0.1 N) or less on the maxillary incisors were sufficient to initiate tipping movement. Whether movement was through bone or the periodontal membrane is not clear.

The results of Reitan's[14] investigations of tooth movement in man and the dog were presented as a relation between total movement and total time. As in Burstone's,[21] and in the author's series of experiments, Reitan's rapid rates of movement in Phase 1 occurred in the first week; after this, in every case, plateaux in the rate-time graphs indicated no further movement for a lengthy period. The low rates in Phase 1 lasted between four and eight days - a result similar to Burstone's[21] and the author's. After eight days tooth movement ceased, again similar to Burstone's and the author's results.

In Reitan's[13] experiments, the low

Table I (v). Fig. 7.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT L.J.			
		BODILY MOVEMENT			
0	450				
7	288	369	1.41	0.48	1.89
14	245	266	0.38	0.30	2.57
21	135	190	1.01	0.60	4.18
28	72	104	0.68	0.63	5.49
35	50	56	0.43	0.00	5.92
			3.91	**2.01**	**5.92**
		TIPPING MOVEMENT			
0	450				
7	337	393	0.96	0.46	1.42
14	265	201	0.35	0.60	2.37
21	98	131	2.31	0.20	4.88
			3.62	**1.26**	**4.88**

rates in Phase 1 lasted from nine to fourteen days - comparable to Smith and Storey's[2] and Storey and Smith's[1] time period, but longer than the author's. Reitan[13] neglected to describe adequately his method of measuring force and distance. In his other experiments,[12,16,17] he mentioned force in only a few of those experiments relating total movement and total time. The slopes of his curves in Phase 2 are comparable to the slopes observed in the author's experiments. Comparisons of the author's results with those of other workers' are impossible because of inadequacies in the design of their experiments.

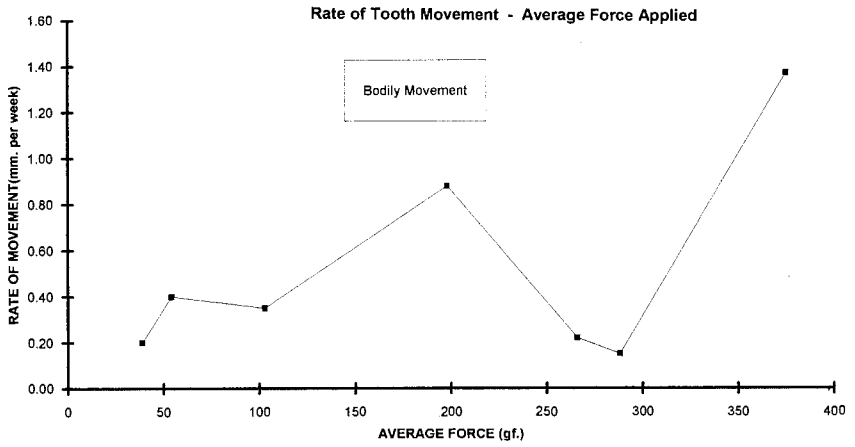
Further investigations of tipping movement are necessary so that the location of the point of application of the force in relation to the length of the tooth and the alveolar crest be controlled; also, so that the load-deflection rates of the springs used in tooth movement be identical in order to eliminate variations in rates of tooth movement incurred by this variable factor. If it were possible to select more accurately the forces required for tooth movement, then, perhaps, future experiments could use smaller helical torsion, coil or some other form of spring made of "super elastic" wire.

This would overcome the likelihood of tissue damage incurred by the use of helical torsion springs with long arms to obtain low rates of force release. The use of centric relation, rather than centric occlusion, would almost certainly improve the stability of the fixed measuring point in the opposing arch, especially in cases where experimental tooth movement causes occlusal interferences. Variations in the occlusal situation, normal drifting of teeth and friction in the buccal tube must have occurred in the author's experiments; however, as these experiments were designed to replicate normal clinical situations, the results must be viewed in this light.

To attain efficiency in orthodontic treatment where tooth movement through bone is required, it is necessary to know the amount of force required to produce tooth movement at optimal rates, that is, at the fastest rate consistent with minimum tissue damage and only that damage which can be repaired. Bone and periodontal membrane can regenerate following tissue damage induced by moderate orthodontic stresses; secondary cementum can repair surface root resorption. Apical root resorption, however, appears to be irreversible. It is obvious from the results of the author's experiments, and those of Storey and Smith[1], Smith and Storey[2] and Burstone,[29] that low rates of release produce the greatest amounts of movement. Therefore, appliances should be designed to incorporate these low rates at force levels that do not induce the low rates of movement in

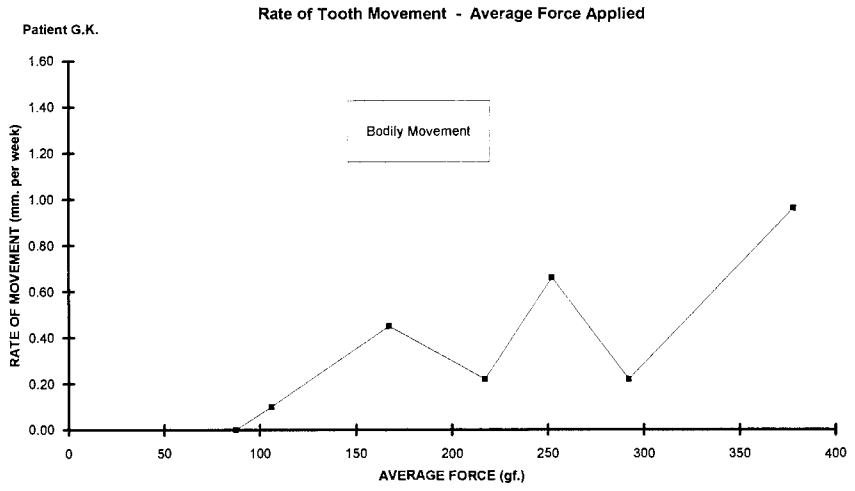
Phase 1 (Burstone's "lag" phase), which Storey[18] presumed are due to undermining resorption caused by excessive stress. The apparently conflicting results of experiments of different researchers may be reconciled when, as Storey and Smith[1] hypothesized, tooth movement is understood in terms of tissue change resulting from the effects of pressure between root and bone, rather than as a result of the application of specific force. The widely differing concepts of "heavy" force held by various researchers - varying from 500 gf [1] (5.0 N) to 1500 gf[24] (15.0 N) - is one example of the need to relate tissue change during tooth movement to the pressures exerted between the tooth root and the surrounding bone. A greater understanding of pressure requirements will make it possible to design orthodontic appliances exerting forces which produce the highest rates of tooth movement consistent with minimal tissue damage.

Table I (vi). Fig. 8.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT R.V.			
		BODILY MOVEMENT			
0	450				
7	300	375	1.37	0.00	1.37
14	277	288	0.15	0.00	1.52
21	255	266	0.22	0.00	1.74
28	142	198	0.88	0.55	3.17
35	65	103	0.35	1.04	4.56
42	43	54	0.40	0.00	4.96
49	35	39	0.20	.000	5.16
			3.57	**1.59**	**5.16**

Table I (vii). Fig. 9.

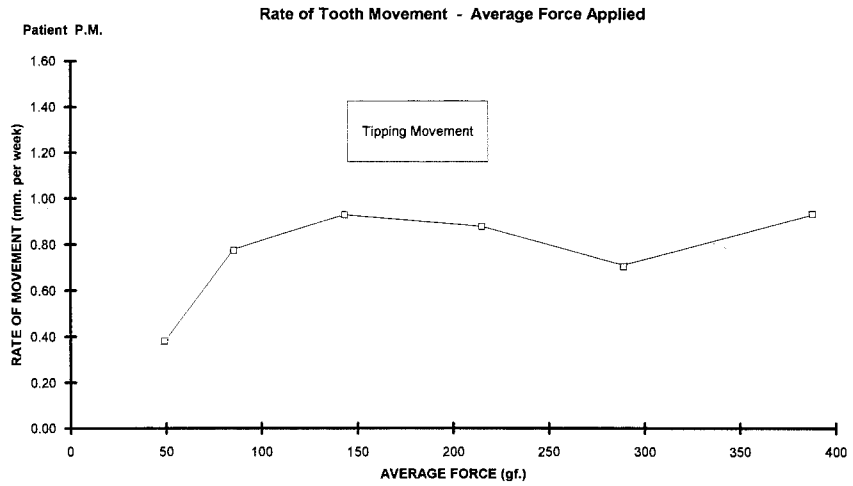


Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT G.K.			
		BODILY MOVEMENT			
0	450				
7	307	378	0.96	0.33	1.29
14	278	292	0.22	0.00	1.51
21	226	252	0.66	0.00	2.19
28	208	217	0.22	0.00	2.39
35	125	167	0.45	0.25	3.09
42	87	106	0.10	0.30	3.49
49	87	87	0.00	0.00	3.49
			2.61	**0.88**	**3.49**

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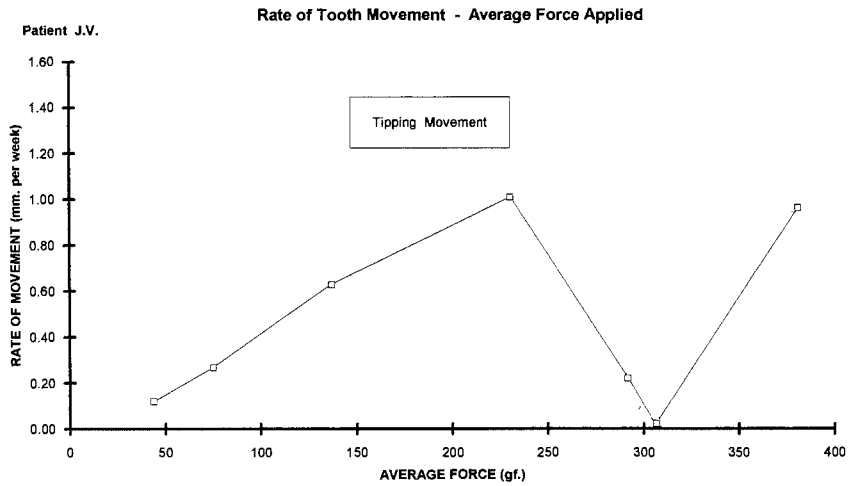
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Table I (viii). Fig. 10.



Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT P.M.			
		TIPPING MOVEMENT			
0	450				
7	327	388	0.93	0.00	0.93
14	252	289	0.71	0.00	1.64
21	178	215	0.88	0.00	2.52
28	108	143	0.93	0.00	3.45
35	63	85	0.78	0.00	4.23
42	35	49	0.38	0.00	4.61
			4.61	**0.00**	**4.61**

Table I (ix). Fig. 11.

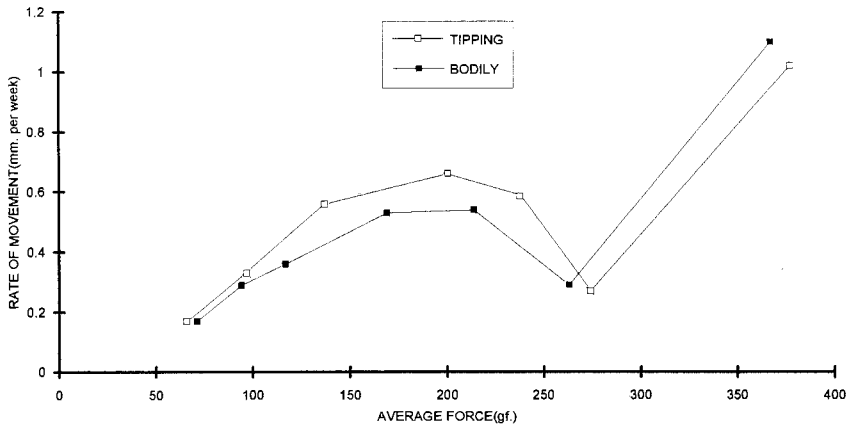


Duration of Movement (Days)	Actual Force (gf)	Average Force (gf)	Amount of Cuspid Movement (mm)	Amount of Anchor Movement (mm)	Total Amount of Space Closure (mm)
		PATIENT J.V.			
		TIPPING MOVEMENT			
0	450				
2	312	381	0.96	0.05	1.01
9	300	306	0.02	0.00	1.03
16	285	292	0.22	0.05	1.30
23	177	231	1.01	0.05	2.36
30	98	137	0.63	0.38	3.37
37	52	75	0.27	0.22	3.86
44	37	44	0.12	0.07	4.05
			3.23	**0.82**	**4.05**

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Table II. Fig. 12.



RELATION BETWEEN AVERAGE FORCE & AVERAGE RATE OF CUSPID TIPPING & BODILY MOVEMENT FOR NINE PATIENTS OVER A SEVEN WEEK PERIOD

BODILY MOVEMENT

Week	1	2	3	4	5	6	7
Average Force (gf)	367	263	214	169	117	94	71
Average Rate of Movement (mm per week)	1.10	0.29	0.54	0.53	0.36	0.29	0.17

TIPPING MOVEMENT

Week	1	2	3	4	5	6	7
Average Force (gf)	377	274	238	200	139	96	66
Average Rate of Movement (mm per week)	1.02	0.27	0.59	0.66	0.56	0.33	0.17

Table III

RANKING OF TOTAL CUSPID TIPPING & BODILY MOVEMENT (IN DESCENDING ORDER) WITH RATES OF RELEASE OF SPRINGS (IN ASCENDING ORDER) USED FOR EACH PATIENT

	Total Cuspid Movement (Bodily)	Rate of Release of Spring	Total Cuspid Movement (Tipping)	Rate of Release of Spring
1	LJ	RV	PM	LJ
2	MW	MW	PL	PL
3	RV	LJ	LJ	PM
4	PL	PL	JV	JV
5	GK	GK	SG	SG
6	SG	SG	MW	MW
7	AL	AL	AL	AL

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