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Systematic review

Surgically facilitated experimental movement of teeth: systematic review

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Abstract

Several surgical techniques based on corticotomy and dental distraction have been developed to improve the movement of teeth and reduce the duration of orthodontic treatment. In this systematic review we have critically assessed published studies on the experimental movement of teeth to find out whether operations such as corticotomy and dental distraction osteogenesis increase the rate of movement, and to find out which biological mechanisms are engaged during surgically facilitated orthodontics, and which complications may be seen. We searched PubMed and Embase for publications until January 2014 and screened the titles and abstracts. Articles that met the inclusion criteria were retrieved in full and assessed independently by 2 of the authors. A total of 22 studies were included, and corticotomy and distraction techniques were the main surgical methods. Generally, all studies reported that movement of teeth was faster after operation than with conventional orthodontics. The peak velocity was always at an early postoperative stage regardless of the surgical technique used. Immunohistological data showed simultaneous regional increases in catabolic and anabolic activity. Histomorphometric data showed more direct resorption of bone and less hyalinisation after operation, and a reduced bone volume density around the surgical site. When present, complications such as root resorption or periodontal problems were minimal. Current experimental animal studies show that procedures such as corticotomy and dental distraction can accelerate the movement of teeth without severe complications because of the regional increase in catabolic and anabolic remodelling.

Keywords: Orthodontics; Corticotomy; Distraction osteogenesis; Accelerated tooth movement; Review

Introduction

Orthodontic treatment aims to improve dentofacial function and aesthetics but patients often complain that it takes a long time to achieve optimal results. To overcome this, surgical techniques have been developed,[1,2] and 2 approaches have been reported to facilitate the movement of teeth. The first is corticotomy in which cortical bone is cut to improve bony remodelling. Periodontally accelerated osteogenic orthodontics, which is a combination of selective alveolar decortications and alveolar augmentation,[3–5] can be modified using selective piezosurgery to circumscribe the roots,[6] and more recently, techniques for minimally invasive flapless corticotomy have been introduced.[1,2]

The second approach is based on distraction osteogenesis, a method described by Ilizarov to induce new bone to form by the mechanical stretching of pre-existing bone.[7] Liou and Huang first applied the concept to the periodontal ligament to facilitate rapid canine retraction in premolar extractions.[8] Kharkar et al. and Işeri et al. described dentoalveolar distraction, which involves decortications around the canines,

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removal of the buccal plate and lining of the extraction socket, and mobilisatioin of the bone block that contains the canine, to achieve rapid retraction.[9–11] Another more invasive procedure is osteotomy distraction, which involves cutting through the cortical and trabecular bone to create a completely separate alveolar segment, followed by application of a continuous distraction force to create a distraction site in the bone.[11]

Both corticotomy-facilitated orthodontics and distraction techniques temporarily improved the movement of teeth with minimal or no complications.[1,3,4,6] Several authors have reported that corticotomy reduced the overall treatment time by between 28% and 70%, and that distraction osteogenesis reduced it by up to 50%.[6,10–12] Canine retraction was achieved within 2 weeks with dentoalveolar distraction and within 3 weeks with distraction of the periodontal ligament, and with both there was minimal loss of anchorage.[8,10,11] Authors of a recent systematic review on human subjects concluded that based on available evidence, surgically facilitated orthodontics seems to shorten treatment time effectively and safely.[13] However, they noted that the level of evidence was limited because of shortcomings in the methodology of the studies included.

Experimental studies can help to overcome some of the limitations of clinical research, and can refine the organisation of clinical studies. Large sample sizes, well-controlled reference groups, and better homogeneity and reproducibility are possible in animal experiments.[14–18] One of the main advantages is that they allow biological mechanisms that underlie improvements in the movement of teeth to be investigated histologically or by micro-computed tomography (CT), or both.[19–21]

Several experimental studies have shown that operations can accelerate the movement of teeth,[14,16,17,22] and histological or immunohistochemical data, or both, have shown regional increases in catabolic and anabolic remodelling with the peak at 1–3 weeks after surgically induced trauma.[19–21] To our knowledge, these studies have not been systematically evaluated and compared.

The aim of this review was to assess published animal studies critically to find out whether operations such as corticotomy and dental distraction osteogenesis significantly increase the movement of teeth. We also aimed to establish the biological mechanisms that are engaged during surgically facilitated orthodontics and to find out which complications may be seen.

Material and methods

Selection criteria

This systematic review was based on the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines.[23] Studies on animals that included operations and velocity of tooth movement or histological analysis were included. Those that described only operations and protocols, or pharmacologically accelerated movement of teeth, or were in languages other than English, German, or Dutch, were excluded.

Information sources

We searched PubMed and Embase for work published until January 2014 using the following keywords rapid tooth movement; corticotomy and orthodontics; corticotomy-facilitated orthodontics; accelerated tooth movement; dentoalveolar distraction; distraction and orthodontics; periodontal distraction and orthodontics; and regional accelerated phenomenon, and orthodontics accelerated osteogenic orthodontics. All eligible studies were checked manually for additional references.

Data extraction

To identify relevant articles, we screened titles and abstracts, and retrieved the full text of papers that met the inclusion criteria. They were then assessed independently for eligibility by 2 authors (AL/YR), and disagreements were resolved by discussion until consensus was reached. Data collection forms were used to compile and present the outcomes of the reviews. Data were collected on the type of operation, number of animals, type of tooth, internal or external control group, and orthodontic force used; and on the frequency of reactivations, rate of tooth movement, incidence of complications, and (immuno)histological or micro-CT outcomes, or both.

Grading of studies

We evaluated the methods used in the studies according to the National Centre for the Replacement, Refinement, and Reduction of Animals in Research (NC3Rs) survey of experimental design and reporting, which is based on the Animal Research: Reporting of In Vivo Experiments (ARRIVE) guidelines.[24,25] This consists of a checklist of essential information that should be included in all experimental studies, and we graded the articles into 3 categories based on the number of items they contained: three-quarters (A), half (B), and a quarter (C). Potential bias was assessed using the Cochrane Collaboration's risk of bias tool.[26] Case studies without controls were not assessed with this tool because the risk of bias is inherently high.

Results

Studies

Our initial searches yielded 154 studies: 94 from PubMed, 58 from Embase, and 2 from hand searches (Fig. 1). After initial application of the exclusion criteria and elimination of duplicates, 137 publications were retrieved. When the full texts were assessed according to the inclusion criteria, 31

Table 1A
Extracted data from experimental studies on the movement of teeth in dogs.

First author, year and reference	Techniques	No. and type of dog	No. of teeth studied	Tooth investigated	Control group	Force (cN)	Latency (days)	Activation	Mean (SD) rate of tooth movement (mm)	Records	Duration of experiment
Teng 2014[32]	Corticotomy mod. 1	6	36	I1, 2, 3U	2 2	0.016x.022 NiTi	0	Once/month	9.57 (0.08) in 3 m	2, 3, 4	3 months
	Orthodontic force only	6	36	I1, 2, 3U		0.016x.022 NiTi	0		4.57 (1.31) in 3 m		
Kim 2013[27]	Corticotomy mod. 3	6 beagles	12	P2U	1&2	CS100	0	Once/week	2.31 (0.82) protraction in 42 d with 1.33 (0.28) AL	3, 4	6 weeks
	Orthodontic force only	4 beagles	8	P2U	1&2	CS100	0		0.72 (0.06) protraction in 42 d with 1.09 (0.07) AL		
	Corticotomy mod. 3		12	P2L	1&2	CS100	0		1.33 (0.28) retraction in 42 d with 0.46 (0.13) AL		
	Orthodontic force only		8	P2L	1&2	CS100	0		0.51 (0.19) retraction in 42 d with 0.40 (0.13) AL		
Liu 2011[38]	DD (extended palatinal bone)	9 beagles	54	I1, 2, 3U	2	JS	0	0.5 mm/day	4.6 (0.1) retraction in 12 d with 1.3 (0.1) AL	1, 4	6 weeks
	Control group (no force)	3 beagles	18	I1, 2, 3U	2	x	x	x	x		
Cohen 2010[30]	DD without segment mobilisation	10 foxhounds	10	P2U	1	JS	0	0.5 mm/day	2.9 protraction in 15 d, 4.4° tipping	1, 3	6 weeks
	PD		10	P2U	1	JS	0		1.8 protraction in 15 d, 3.9° tipping		
Sanjideh 2010[28]	Corticotomy mod. 1	5 foxhounds	5	P3U	1	CS 200	0	Once/2 weeks	2.0 protraction in 56 d	1, 3	8 weeks
	2nd corticotomy mod. 1		5	P3U	1	CS 200	0		2.3 protraction in 56 d		
	Corticotomy mod. 1		5	P2L	1	CS 200	0		2.4 retraction in 56 d		
	Orthodontic force only		5	P2L	1	CS 200	0		1.3 retraction in 56 d		
Mostafa 2009[33]	Corticotomy	6	6	P1U	1	CS 400	0	–	4.7 (0.6) retraction in 28 d	3, 4	6 weeks
	Orthodontic force only		6	P1U	1	CS 400	0	–	2.3 (0.6) retraction in 28 d		
Kim 2009[31]	Corticotomy mod. 3	12 beagles	6	P2U	1&2	CS 150	0	Once/week	4.6 (0.3) protraction in 56 d, 1.3 (0.2) AL	3, 4	8 weeks
	Laser therapy		6	P2U	1&2	CS 150	0		4.6 (0.3) protraction in 56 d, 1.4 (0.2) AL		
	Laser therapy + corticotomy mod. 3		6	P2U	1&2	CS 150	0		0.9 (0.2) protraction in 56 d, 1.1 (0.1) AL		
	Orthodontic force only		6	P2U	1&2	CS 150	0		1.2 (0.2) protraction in 56 d, 0.8 (0.1) AL		
Lv 2009[22]	PD	8 beagles	8	P1L	1	JS	0	0.5 mm/day	5.0 (0.1) retraction in 14 d, slight tipping, 0.3 (0.1) AL	3, 4	8 weeks
	Orthodontic force only		8	P1L	1	CS 100	0	–	1.1 (0) retraction in 28 d, slight tipping, 0.5 (0.04) AL		

Table 1A (*Continued*)

First author, year and reference	Techniques	No. and type of dog	No. of teeth studied	Tooth investigated	Control group	Force (cN)	Latency (days)	Activation	Mean (SD) rate of tooth movement (mm)	Records	Duration of experiment
Ai 2008[34]	PD	8	8	P1L	1	JS	0	0.5 mm/day	3.7 (0.1) retraction in 14 d, 16.5° (4.6) tipping, minimal AL	1, 3, 4	10 weeks
	Orthodontic force only		8	P1L	1	CS 100	0	Once/2 weeks	1.2 (0.2) retraction in 14 d, 11.5° (3.4) tipping, minimal AL		
Han 2008[35]	PD	8 beagles	8	P1L	1	CS 100	0	–	1.9 (0) retraction in 28 d, minimal AL	3, 4	8 weeks
	Orthodontic force only		8	P1L	1	CS 100	0	–	1.0 (0.1) retraction in 28 d, minimal AL		
Cho 2007[36]	Corticotomy mod. 2	2 beagles	2	P3U	1	CS 150	0	–	6.4 retraction in 56 d	3, 4	6 months
	Corticotomy mod. 2		2	P3L	1	CS 150	0	–	3.3 retraction in 56 d		
	Orthodontic force only		2	P3U	1	CS 150	0	–	1.45 retraction in 56 d		
	Orthodontic force only		2	P3L	1	CS 150	0	–	1.35 retraction in 56 d		
Iino 2007[18]	Corticotomy mod. 1	12 beagles	12	P3L	1	CS 50	0	Once/week	2 protraction in 28 d, slight tipping	1, 4	8 weeks
	Orthodontic force only		12	P3L	1	CS 50	0		1 protraction in 28 d, slight tipping		
Ren 2007[37]	PD	10 beagles	10	P1L	1	CS 150	0	–	4.3 (0.5) retraction in 28 d, minimal AL	1, 3, 4	8 weeks
	Orthodontic force only		10	P1L	1	CS 150	0	–	2.0 (0.4) retraction in 28 d, minimal AL		
Düker 1975[39]	Corticotomy mod. 1	6 beagles	12	I1U	0	Elastics	0	–	4 protraction of segment (bone + incisors) in 8–20 d	1, 5	16 weeks

d = days; w = weeks; m = months.
Technique: Corticotomy mod. 1, Corticotomy mod. 2, Corticotomy mod. 3; PD = periodontal distraction; DD = dentoalveolar distraction osteogenesis, osteotomy distraction.
Tooth investigated: U = upper arch; L = lower arch; I = incisor; C = canine; P = premolar; M = molar; number indicates 1st, 2nd, or 3rd (pre)molar.
C: control group: 0 = no control; 1 = internal control; 2 = external control.
Force: JS = jackscrew; CS = coilspring; x = no force.
Rate of tooth movement: AL: loss of anchorage, minimal AL = less than 1 mm lost.
Records: diagnostic records taken: 1 = X-ray; 2 = CT; 3 = caliper measurements; 4 = histological/immunohistochemical analysis; 5 = vascular system filled with Plastoid followed by partial maceration to visualise it.

Table 1B
Extracted data from experimental studies on the movement of teeth in rats.

First author, year and reference	Techniques	No. of rats	No. of teeth studied	Tooth investigated	Control group	Force (cN)	Latency (days)	Activation	Mean (SD) rate of tooth movement (mm)	Records	Duration of experiment (weeks)
Iglesias-Linares 2012[14]	Corticotomy	56	16	M2U	1&2	CS 10	0	–	0.6 palatal displacement in 14 d; 0.8 in 32 d	3, 4	4.5
	Corticotomy BMP-2 injections		16	M2U	1&2	CS 10	0	–	0.4 palatal displacement in 14 d; 0.6 in 32 d		
	BMP-2 injections only		16	M2U	1&2	CS 10	0	–	0.3 palatal displacement in 14 d; 0.6 in 32 d		
	Orthodontic force only		64	M2U	1&2	CS 10	0	–	0.3 palatal displacement in 14 d; 0.5 in 32 d		
Iglesias-Linares 2011[15]	Corticotomy	72	16	M2U	1&2	CS 10	0	–	0.5 palatal displacement in 14 d; 0.7 in 32 d	3, 4	4.5
	Corticotomy without force		16	M2U	1&2	x	x	–	0.4 palatal displacement in 14 d; 0.5 in 32 d		
	RANKL gene transfection injections		16	M2U	1&2	x	x	–	0		
	RANKL gene transjection +force		16	M2U	1&2	CS10	0	–	0.6 palatal displacement in 14 d; 0.9 in 32 d		
	Orthodontic force only		8	M2U	1&2	CS 0-10	0		0.4 palatal displacement in 14 d; 0.5 in 32 d		
Baloul 2011[20]	Corticotomy mod. 2	114	36	M1U	2	CS 25	0	Once	Not exactly specified; no lag phase, direct linear displacement	1, 2, 4	7
	Corticotomy mod. 2 without force		36	M1U	2	x	x	Once	x		
	Orthodontic force only		36	M1U	2	CS 25	0		Not exactly specified		
Teixeira 2010[16]	Corticotomy mod.2	48	12	M1U	1&2	CS 50	0	Once/2 weeks	0.6 protraction in 28 d	2, 4	4
	Orthodontic force + flap		12	M1U	1&2	CS 50	0		0.3 protraction in 28 d		
	Orthodontic force only		12	M1U	1&2	CS 50	0		0.3 protraction in 28 d		
	Control group (no force)		12	M1U	1&2	x	0		0		
Wang 2009[19]	Corticotomy mod.1	36	8	M1U	1&2	CS 100	2	–	No rate described	4	8.5
	Corticotomy without force		7	M1U	1&2	x	x				
	Osteotomy distraction		8	M1U	1&2	CS100	2	–			
	Osteotomy distraction without force		7	M1U	1&2	x	x				
	Orthodontic force only		6	M1U	1&2	CS100	2	–			

Table 1B (*Continued*)

First author, year and reference	Techniques	No. of rats	No. of teeth studied	Tooth investigated	Control group	Force (cN)	Latency (days)	Activation	Mean (SD) rate of tooth movement (mm)	Records	Duration of experiment (weeks)
Sebaoun 2008[21]	Corticotomy	36	18	M1U	1&2	x	x	–	No rate described	4	7/11
	Corticotomy + bone stain injections (till 4 wk)		18	M1U	1&2	x	x	–			
	Corticotomy + bone stain injections (till 7wk)		18	M1U	1&2	x	x	–	0.3 protraction in 21 d	2, 3	8.5
	Corticotomy+ calcein stain.		6	M1U	1&2	CS 100	3	–	0		
Lee 2008[29]	Corticotomy mod. 1	30	6	M1U	1&2	x	x		0.4 protraction in 21 d		
	Corticotomy mod.1 without force		6	M1U	1&2	CS 100	3	–	0		
	Osteotomy distraction		6	M1U	1&2	x	x		0.3 protraction in 21 d		
	Osteotomy distraction without force		6	M1U	1&2	CS 100	3	–			
	Orthodontic force only										

See Table 1A legend.

were selected, and after further assessment 22 remained (14 on dogs, 7 on rats, and 1 on cats) with corticotomy or distraction as the main procedure. A summary of the data from the 21 articles is given in Tables 1A and 1B. A description of the techniques used in them is shown in Fig. 2.

Grading of studies

Most of the studies were of moderate quality (B), but 5 were graded as high (A) and one as low quality (C). The reasons why most of the studies were graded as moderate were because outcome assessments were not blinded, sample sizes were not identified or justified, methods of randomisation were not stated, or no raw data were available (Table 2). All studies were assessed to have a certain risk of bias (Table 3).

Movement of teeth

In general, all the studies except the one on cats (no data on movement of teeth) reported faster movement after operation than with the use of conventional experimental interventions (Tables 1A and 1B). The peak velocity was always shortly after operation regardless of the technique used, and it ranged from 2 to 3 weeks after the intervention.[17,18,22,27] One study reported that a second corticotomy after 4 weeks maintained the improved velocity of movement for a longer period, but the difference in terms of overall duration of treatment was small compared with the outcome after a single operation.[28] Lee et al. directly compared corticotomy with osteotomy distraction and reported a slightly higher rate of movement with osteotomy distraction.[29] Distraction of the periodontal ligament was compared directly with dentoalveolar distraction in only one study, and a faster rate of movement was seen with the latter.[30] In 2 studies, the effect of corticotomy combined with an additional intervention was investigated. When corticotomy was combined with supplementary low-level laser treatment, it inhibited the movement of teeth although each technique alone had an accelerating effect. When combined with injection of bone morphogenetic protein 2 (BMP-2) there was no synergistic acceleratory effect on movement.[14,31]

Histological and immunohistological results

Most of the studies reported an increase in both osteoclastic and osteoblastic activities (Tables 4A and 4B).[14,15,17,18,20–22,31–34] Teng et al. analysed biomarkers of bony remodelling after corticotomy and found a regional increase in GCF-bALP and GCF-ICTP in the experimental group. Serum-bALP and serum-ICTP concentrations remained unchanged, which indicated that the operation did not induce a systemic increase in bony turnover.[32] Several studies reported a peak in osteoclast and osteoblast recruitment at an early stage after surgical stimulation.[16,18–22,35] In contrast, corticotomy combined with an additional technique (low-level laser treatment

Table 2
Grading of studies (A: ratio yes/no 3 or more; B: ratio yes/no 1 or more; C: ratio yes/no less than 1).

	Purpose introduction	Sex reported	Strain/species reported	Factorial design	Type experiment between subjects	Type experiment within subject	Randomisation appropriate	Measurements blinded	Numerical data	Statistical methods reported in methods section
Teng 2014[32]	Y	Y	Y	N	Y	N	?	N	Y	Y
Kim 2013[27]	Y	Y	Y	N	Y	Y	?	Y	Y	Y
Liu 2011[38]	Y	Y	Y	N	Y	N	?	N	Y	Y
Cohen 2010[30]	Y	Y	Y	N	N	Y	?	N	Y	Y
Sanjideh 2010[28]	Y	Y	Y	Y	Y	Y	?	Y	Y	Y
Mostafa 2009[33]	Y	N	N	N	Y	Y	?	N	Y	Y
Kim 2009[31]	Y	Y	Y	Y	Y	Y	?	Y	Y	Y
Lv 2009[22]	Y	Y	Y	N	Y	Y	?	N	Y	Y
Ai 2008[34]	Y	Y	Y	N	Y	Y	?	N	Y	Y
Han 2008[35]	Y	Y	Y	N	Y	Y	?	Y	Y	Y
Cho 2007[36]	Y	N	Y	Y	Y	Y	?	N	Y	N
Iino 2007[18]	Y	Y	Y	N	Y	Y	?	N	Y	Y
Ren 2007[37]	Y	Y	Y	N	Y	Y	?	N	Y	Y
Düker 1975[39]	Y	Y	Y	N	N	N	N	N	Y	N
Iglesias-Linares 2012[14]	Y	N	Y	N	Y	Y	?	N	Y	Y
Iglesias-Linares 2011[15]	Y	N	Y	Y	Y	Y	?	N	Y	Y
Baloul 2011[20]	Y	N	Y	Y	Y	N	?	N	Y	Y
Teixeira 2011[16]	Y	Y	Y	Y	Y	Y	?	N	Y	Y
Wang 2009[19]	Y	N	Y	Y	Y	Y	?	N	Y	Y
Sebaoun 2008[21]	Y	Y	Y	N	Y	Y	?	N	Y	Y
Lee 2008[29]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y

	Statistical methods reported in results section	Hypotheses defined	Method of randomisation stated	Blocking appropriate	Sample size correctly identified	Sample size justified	Equal sample size groups	Number of groups stated in all figures and tables	Subjective scores used	Subjective scores blinded
Teng 2014[32]	Y	Y	N	Y	Y	N	Y	Y	Y	N
Kim 2013[27]	Y	N	N	Y	N	N	N	Y	Y	N
Liu 2011[38]	Y	Y	N	Y	Y	N	N	N	Y	N
Cohen 2010[30]	Y	Y	N	Y	Y	N	Y	Y	N	-
Sanjideh 2010[28]	Y	Y	N	Y	Y	N	Y	Y	N	N
Mostafa 2009[33]	Y	N	N	?	?	N	Y	Y	Y	N
Kim 2009[31]	Y	N	N	Y	Y	N	Y	Y	Y	Y
Lv 2009[22]	Y	N	N	Y	Y	N	Y	Y	Y	N
Ai 2008[34]	Y	N	N	?	N	N	Y	Y	Y	N
Han 2008[35]	Y	Y	N	Y	Y	N	Y	Y	Y	Y
Cho 2007[36]	N	N	N	?	?	N	Y	Y	Y	N
Iino 2007[18]	Y	N	N	?	Y	N	Y	Y	Y	N
Ren 2007[37]	Y	N	N	Y	Y	N	Y	Y	Y	N
Düker 1975[39]	N	N	N	N	N	N	-	N	Y	N
Iglesias-Linares 2012[14]	Y	N	N	?	N	N	N	Y	Y	N

Table 2 (*Continued*)

	Statistical methods reported in results section	Hypotheses defined	Method of randomisation stated	Blocking appropriate	Sample size correctly identified	Sample size justified	Equal sample size groups	Number of groups stated in all figures and tables	Subjective scores used	Subjective scores blinded
Iglesias-Linares 2011[15]	Y	Y	N	?	N	N	N	Y	Y	N
Baloul 2011[20]	Y	Y	N	N	?	N	Y	Y	Y	N
Teixeira 2011[16]	Y	Y	N	Y	Y	N	Y	Y	Y	N
Wang 2009[19]	Y	N	N	N	?	N	N	Y	Y	Y
Sebaoun 2008[21]	Y	N	N	N	N	N	Y	Y	Y	N
Lee 2008[29]	Y	N	N	N	N	N	Y	Y	Y	N

	Graphs/tables clearly titled	Graphs/tables clearly labelled	Graphs appropriate	Tables appropriate	Raw data available	Number treatment groups appropriate	Design appropriate	Conclusions justified	Source of funding described	Grade
Teng 2014[32]	Y	Y	Y	Y	N	Y	Y	Y	Y	A
Kim 2013[27]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Liu 2011[38]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Cohen 2010[30]	Y	Y	Y	Y	N	Y	Y	Y	Y	B
Sanjideh 2010[28]	Y	Y	Y	Y	N	Y	Y	Y	Y	A
Mostafa 2009[33]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Kim 2009[31]	Y	Y	Y	Y	N	Y	Y	Y	N	A
Lv 2009[22]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Ai 2008[34]	Y	Y	N	Y	N	Y	Y	Y	N	B
Han 2008[35]	Y	Y	Y	Y	N	Y	Y	Y	N	A
Cho 2007[36]	Y	Y	Y	Y	N	N	Y	Y	N	B
Iino 2007[18]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Ren 2007[37]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Düker 1975[39]	N	N	N	N	N	N	N	Y	N	C
Iglesias-Linares 2012[14]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Iglesias-Linares 2011[15]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Baloul 2011[20]	Y	Y	Y	Y	N	Y	Y	Y	N	B
Teixeira 2011[16]	Y	Y	Y	Y	N	Y	Y	Y	N	A
Wang 2009[19]	Y	Y	Y	Y	N	Y	Y	Y	Y	B
Sebaoun 2008[21]	Y	Y	Y	Y	N	Y	N	Y	Y	B
Lee 2008[29]	N	Y	Y	Y	N	Y	N	Y	N	B

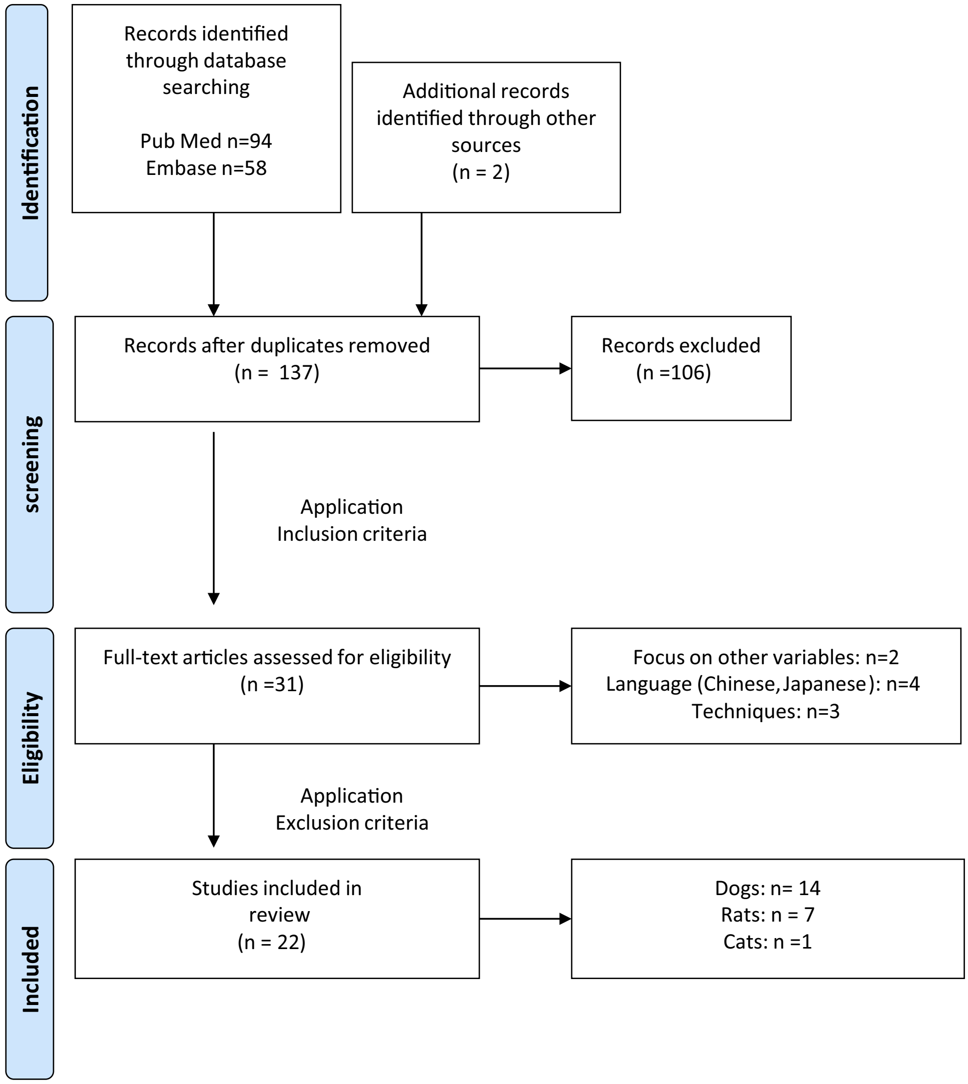

Fig. 1. Flow chart to show selection of articles.

or injection of BMP-2), resulted in a reduction of both catabolic and anabolic bony turnover compared with the controls, which was in line with the observed velocity of tooth movement.[14,31] Cho et al. investigated the long-term effect of both osteoclastic and osteoblastic activities after operation, and reported that activity decreased after 6 months of cortical activation.[36]

Histomorphometric data showed more direct bony resorption and less pronounced hyalinisation with operation, and a reduction in bone volume density around the surgical site.[14–16,18,22,31,33,34,37] Two studies noted site-specific differences in bone marker expression and resorption of bone between different operations. With corticotomy, there was regional loss of bone density around the roots whereas with distraction, remodelling occurred exclusively at the distraction gap.[19,21,29] In other studies, corticotomy induced an increase in bone apposition on the tension side, and there was a difference in the quality and thickness of the alveolar bone with bulky and lamellar bone in the corticotomy group and thin and woven bone in the control group not operated on.[22,27,33,37] In line with these results, Baloul et al. reported increased bone mineral volume and bone mass during the tooth movement phase, and observed that homeostasis was restored to baseline levels 7 weeks postoperatively with no pathological loss of bone density, mass, and volume.[20]

Kim et al. investigated the biological effects of a minimally invasive corticotomy technique in cats, and reported increased catabolic and anabolic remodelling activities.[17] Their results were consistent with the findings of more invasive techniques in dogs and rats.

Complications

No complications were reported in the studies on rats and cats (Table 5). In the experiments on dogs, root resorption was assessed in all studies on distraction and in 2 on corticotomy.[18,22,30,33,34,37,38] After treatment there was no difference in the length of roots between the surgical and

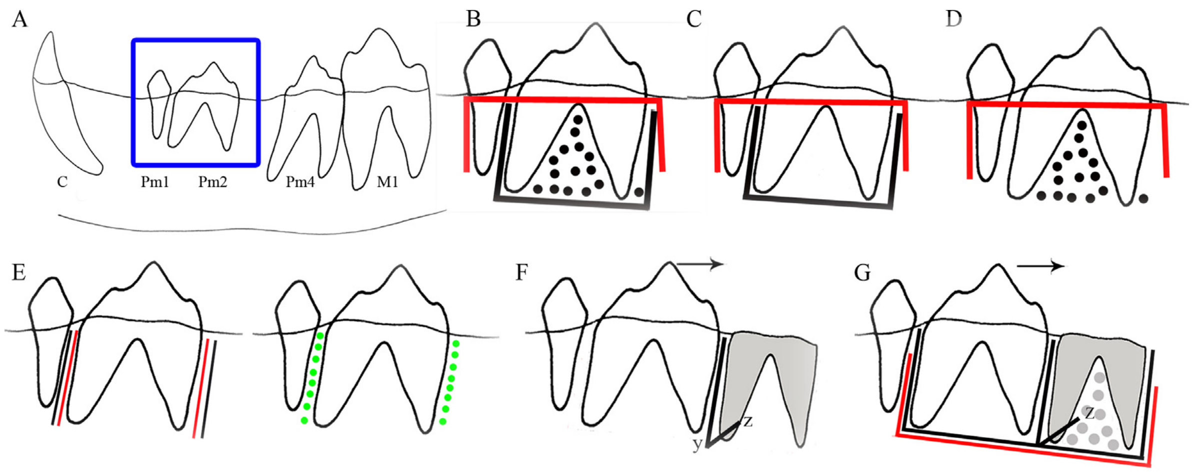

Fig. 2. Surgical techniques (buccal view): (A) Anatomy of dog's mandible: showing the C, Pm_1, Pm_2, Pm_4 and M_1. The blue square is magnified and used to illustrate the different techniques in diagrams B–G. (B) Corticotomy: mucoperiosteal flaps are raised (red incision line). Circumscribing decortications on the buccal or lingual side, or both (black lines and dots). (C) Corticotomy modification 1. Monocortical (piezo) surgery: mucoperiosteal flap (red incision line) and circumscribing cuts with ultrasonic bone saw (black lines). (D) Corticotomy modification 2. Monocortical perforations: mucoperiosteal flap (red incision line) and cortical perforations (black dots) in area(s) of intended tooth movement. (E) Corticotomy modification 3. Piezocision/piezopuncture: small vertical incisions (red lines) and vertical cuts (black lines) or cortical punctures (green dots) through the gingiva into the cortical bone. (F) Distraction of the periodontal ligament: directly after extraction of third premolar (grey shading) vertical grooves are cut through the lingual and vestibular walls of the socket (y-line), and then connected by an oblique cut through the apical part of the alveolus (z-line). No flaps are raised. (G) Dentoalveolar distraction: a vestibular flap is raised (red line). Cuts outlining the second premolar (black lines) are made and locally extended to the lingual plate (z-line). The extracted third premolar (grey shading), the buccal plate lining the extraction socket and bony interferences are removed (grey dots). Osteotomy: similar design to dentoalveolar distraction except that cuts are made completely through the lingual plate, and the chisel used to create a separate alveolar segment.

Table 3
Risk of bias. It was not clear whether they were free from other forms of bias.

Studies	Adequate sequence generation	Allocation concealment	Blinding	Incomplete outcome data addressed	Free from selective reporting
Teng 2014[32]	Unclear	Unclear	High	Low	Low
Kim 2013[27]	Unclear	Unclear	High	Low	Low
Liu 2011[38]	Unclear	Unclear	High	High	Low
Cohen 2010[30]	Unclear	Unclear	High	Low	Low
Sanjideh 2010[28]	Unclear	Unclear	High	Low	Low
Mostafa 2009[33]	High	High	High	Low	Low
Kim 2009[31]	Unclear	Unclear	Low	Low	Low
Lv 2009[22]	High	High	High	Low	Low
Ai 2008[34]	Low	Unclear	High	Low	Low
Han 2008[35]	Unclear	Unclear	Low	Low	Low
Cho 2007[36]	High	High	High	Low	Low
Iino 2007[18]	High	High	High	Low	Low
Ren 2007[37]	Unclear	Unclear	High	Low	Low
Düker 1975[39]	High	High	High	High	High
Iglesias-Linares 2012[14]	Unclear	Unclear	High	Unclear	Unclear
Iglesias-Linares 2011[15]	High	High	High	Unclear	Unclear
Baloul 2011[20]	High	High	High	Low	Low
Teixeira 2010[16]	High	High	High	Low	Low
Wang 2009[19]	High	High	Low	Low	Low
Sebaoun 2008[21]	High	High	High	Low	Low
Lee 2008[29]	High	High	High	Low	Low

Table 4A
Histological findings: dog studies.

	Techniques	Histological variables	Markers/staining	Results
Teng 2014[32]	Corticotomy mod.1 Orthodontic force only	Bony resorption	CBCT images	Osteotomy group showed increased regional osteoclastic and osteoblastic activities, and increased bony resorption. No difference between both groups in systemic bony turnover.
		Osteoclastic Osteoblastic	Serum bALP, GCF bALP Serum ICTP, GCF ICTP	
Kim 2013[27]	Corticotomy mod. 3 Orthodontic force only	Bony resorption Hyalinisation Bone apposition	H&E staining H&E staining Fluorescent bone markers with oxytetracycline hydrochloride, calcein, alizarin red staining	Corticotomy group showed increased bony resorption and appositional activities, and less pronounced hyalinisation
Liu 2011[38]	DD (extended palatal bone) Control group (no force)	Bony remodelling Hyalinisation	H&E staining H&E staining	Dentoalveolar distraction group showed increased bony remodelling, a small area of hyalinisation, and undermining resorption
Mostafa 2009[33]	Corticotomy Orthodontic force only	Bony resorption Osteoclast Collagen degeneration	H&E staining H&E staining Masson's trichrome staining	Corticotomy group showed increased bony resorption and osteclasts, and pronounced degeneration of collagen
Kim 2009[31]	Corticotomy mod. 3 Low-level laser therapy Laser therapy + Corticotomy mod. 3 Orthodontic force only	(Pre)osteoclast Osteoblast Bone apposition	H&E and TRAP staining H&E and PCNA staining Fluorescent bone markers with oxytetracylcine hydrochloride, calcein, alizarin red staining	Low-level laser treatment showed most increase in (pre)osteoclasts and osteoblasts and appositional activities. Corticotomy showed greater increase in (pre)osteoclasts and osteoblasts and appositional activities compared with force alone
Lv 2009[22]	PD Orthodontic force only	Osteoclast and its precursors Bony resorption Hyalinisation Bone apposition	TRAP staining H&E staining H&E staining Masson's trichrome staining	Periodontal ligament distraction group showed increased bony resorption, osteoclasts, and appositional activities, and also less pronounced hyalinisation
Ai 2008[34]	PD Orthodontic force only	Hyalinisation Osteoclast Osteoblast	H&E staining H&E staining H&E staining	Periodontal ligament distraction group showed increased osteoblasts and osteoclasts, and less pronounced hyalinisation
Han 2008[35]	PD Orthodontic force only	Osteocalcin	Osteocalcin antibody	Periodontal ligament distraction group showed increased density of osteocalcin
Cho 2007[36]	Corticotomy mod. 2 Orthodontic force only	Osteoclast Osteoblast Fibroblast	Double staining of methylene blue with uranyl acetate and lead citrate Double staining of methylene blue with uranyl acetate and lead citrate Double staining of methylene blue with uranyl acetate and lead citrate	Corticotomy group showed greater increase in osteoclasts, osteoblasts, and fibroblasts.
Iino 2007[18]	Corticotomy mod. 1 Orthodontic force only	Bony resorption Osteoclast Hyalinisation	H&E staining TRAP staining with methylene blue H&E staining	Corticotomy group showed increased bony resorption and osteoclasts, and also less pronounced hyalinisation
Ren 2007[37]	PD Orthodontic force only	Bone apposition Hyalinisation Bony resorption	Fluorescent microphotographs analysed by pixels Toluidine blue staining Toluidine blue staining	Periodontal ligament distraction showed increased bony resorption and appositional activities, and less pronounced hyalinisation

Table 4B
Histological findings: rat studies.

	Techniques	Histological variables	Markers/staining	Results
Iglesias-Linares 2012[14]	Corticotomy Corticotomy + BMP-2 injection BMP-2 injections only Orthodontic force only	Bony resorption Osteoclast	H&E staining TRAP staining	Corticotomy group showed increased bony resorption and osteoclasts
Iglesias-Linares 2011[15]	Corticotomy Corticotomy without force RANKL gene transfection injections RANKL gene transjection +force Orthodontic force only	Bony resorption Osteoclast RANKL	H&E staining TRAP staining RANKL antibody	RANKL gene transfection group with force showed most increase in osteoclasts and RANKL, and more bony resorption. Corticotomy group showed increased osteoclasts, RANKL, and more bony resorption compared with force alone
Baloul 2011[20]	Corticotomy mod. 2 Corticotomy mod. 2 without force Orthodontic force only	Loss of bony volume	Micro-CT images analysed by bone voxels in Hounsfield units to mineral values (mg/ml of hydroxyapatite).	Corticotomy group showed most loss of bony volume, and mass in early stadium and most increase in osteoclastic and osteoblastic activities in early stadium, but no difference among the groups in bone mineral density.
		Bone mineral density	Micro-CT images analysed by bone voxels, bone voxels above the threshold (voxels considered to be bone tissue)	
		Bone mineral content	Micro-CT images analysed by bone voxels, bone voxels above the threshold (voxels considered to be bone)	
		Osteoclastic	Osteoclast regulation markers M-CSF, OPG, RANKL, TRACP 5b, CtsK, CTR by q-PCR	
		Osteoblastic	Osteoblast regulation markers BSP, OPN, OCN by q-PCR	
Teixeira 2010[16]	Corticotomy mod.2 Orthodontic force + flap Orthodontic force only No orthodontic force	Cytokines Osteoclasts Loss of bone	RT-PCR TRAP staining Micro-CT images with the ratio of bone volume to total volume calculated (BV/TV)	Corticotomy group showed increased loss of bone and increase in osteoclasts and cytokines. No differences among force only group and force with flap group.
Wang 2009[19]	Corticotomy Corticotomy without force Osteotomy distraction Osteotomy distraction without force Orthodontic force only	Bony resorption Osteoblast Osteoclast Blood vessels	H& E staining PCNA, TGF-beta 1, osteocalcin staining PCNA, TGF-beta 1, osteocalcin staining H&E staining	Corticotomy group showed most increase in bony resorption and osteoblastic and osteoclastic activities in early stadium, and also increase in blood vessels. Immunostaining pattern was strongest in the corticotomy group at the mesial site, in the osteotomy group at the distal distraction site
Sebaoun 2008[21]	Corticotomy Control group (no force)	Loss of bone PDL surface (Pre)osteoclast Formation of bone Bone apposition	H&E staining H&E staining TRAP staining Calcein fluorescent staining Calcein, tetracycline and alizarin red staining	Corticotomy group showed increased bony resorption and greater PDL surface, and also more (pre)osteoclasts, increased bony formation and appositional activities in early stadium
Lee 2008[29]	Corticotomy mod. 1 Corticotomy mod. 1 without force Osteotomy distraction Osteotomy distraction without force Orthodontic force only	Loss of bone	Micro-CT images analysed by pixels	Corticotomy without force group showed most loss of bone. Orthodontic force only showed least loss. In both corticotomy groups more regional bone was lost, in the osteotomy groups more bone was lost at the distal site

Technique: Corticotomy mod. 1, mod. 2, mod. 3; PD = periodontal distraction; DD = dentoalveolar distraction osteogenesis, osteotomy distraction.
Serum bALP = serum bone-specific alkaline phosphatase; GCF bALP = gingival crevicular fluid bone-specific alkaline phosphatase; ICTP = C-terminal telopeptide of type I collagen; GCF ICTP = gingival crevicular fluid C-terminal telopeptide of type I collagen; H&E = haematoxylin and eosin; TRAP staining = tartrate-resistant acid phosphatase staining; RANKL = receptor activator of nuclear factor kappa-B ligand; PCNA = proliferating cell nuclear antigen; M-CSF = macrophage colony-stimulating factor; TRACP 5b = tartrate-resistant acid phosphatase 5b; CtsK = cathepsin K; CTR = calcitonin receptor; BSP = bone sialoprotein; OPN = osteopontin; OCN = osteocalcin; TGF-beta 1 = transforming growth factor beta 1; RT-PCR = reverse transcription polymerase chain reaction.

Table 5
Complications.

First author, year, and reference	Techniques	No. of subjects	No. of teeth studied	Tooth investi-gated	Control group	Complications	Duration of experiment (weeks)
Liu 2011[38]	Dentoalveolar distraction osteogenesis, extended palatal bone Control group (no force)	9 3	54 18	I1, 2, 3U I1, 2, 3U	2 2	Root resorption Dentoalveolar distraction osteogenesis: slight lateral root surface irregularities compression side, slight blunting of the apex I3.	6
Cohen 2010[30]	Dentoalveolar distraction osteogenesis without segment mobilisation Periodontal distraction	10	10 10	P2U P2U	1 1	Root resorption Dentoalveolar distraction osteogenesis: mesial 0.09 mm; distal 0.16 mm in 28 d Periodontal distraction: mesial 0.09 mm; distal 0.14 mm in 28 d	6
Sanjideh 2010[28]	Corticotomy mod. 1 2nd corticotomy mod. 1 Corticotomy mod. 1 Orthodontic force only	5	5 5 5 5	P3U P3U P2L P2L	1 1 1 1	Hyperaemia Both groups showed no hyperaemia Periodontal problems Both groups showed no recession of the tissues	8
Mostafa 2009[33]	Corticotomy Orthodontic force only	6	6 6	P1U P1U	1 1	Root resorption Both groups had no root resorption	6
Lv 2009[22]	Periodontal distraction Orthodontic force only	8	8 8	P1L P1L	1 1	Root resorption Periodontal distraction: small regions at 4 wk, partial repair 8 wk both sides	8
Ai 2008[34]	Periodontal distraction Orthodontic force only	8	8 8	P1L P1L	1 1	Root resorption 4 P1L slight blunting of the apex at 14 d (3 periodontal distraction, 1 control) 1 PIL slight lateral root resorption.	10
Iino 2007[18]	Corticotomy mod. 1 Orthodontic force only	12	12 12	P3L P3L	1 1	Root resorption No root resorption corticotomy group Control group: root resorption around area of hyalinisation at 28 d and more striking at 56 d.	8
Ren 2007[37]	Periodontal distraction Orthodontic force only	10	10 10	P1L P1L	1 1	Hyperaemia Both groups mild hyperaemia P1L at 56 d, no necrosis Root resorption Small regions of root resorption at 28 d, partial repair at 56 d.	8
Düker 1975[39]	Corticotomy mod. 1	6	12	I1U	0	Periodontal problems 2 dogs slightly deepened pockets	16

Control group: 0 = no control; 1 = internal control; 2 = external control.

control groups. Iino et al. reported less root resorption in the corticotomy group,[18] and Ren et al. reported mild hyperaemia with periodontal distraction, but there was no necrosis of the pulp.[37] In a case study on corticotomy, Düker reported slightly deepened pockets.[39]

Discussion

To our knowledge, this is the first systematic review on the surgically facilitated experimental movement of teeth. All the studies reported that movement was faster after operation than with conventional orthodontics and the histological data showed a simultaneous increase in both catabolic and anabolic activities. However, the overall scientific quality of the studies was only moderate.

Animals as experimental models

Dogs or rats, which are the most commonly used experimental animals, were used in most of the studies as they offer generally good homogeneity and reproducibility to overcome the limitations of clinical studies. However, the morphological and physiological differences in alveolar bone and periodontal ligaments between animals and humans must be considered. Alveolar bone in dogs is generally denser than in humans although the difference between the anatomy of the periodontal ligament and alveolar bone in dogs and humans is rather small.[40,41] In rats, the alveolar bone shows no osteons, its bone plates lack marrow spaces, and the bone is denser than that in humans. Also, the osteoid tissue along the surface of the bone is generally less abundant than in humans.[42] Despite these differences, rats and dogs are generally considered to be good animal models for experimental studies on the movement of teeth, and the results can be extrapolated to human situations when the limitations of the study design are acknowledged.[41,42]

In general, the results on the movement of teeth in the studies included are in line with those reported in a recent review on similar operations in humans.[13]

Effect of surgical techniques

The studies in this review include a variety of surgical designs and different extents of operation. Despite such variations, all the operations improved the movement of teeth, although 2 reported a significantly higher rate of movement in the upper jaw.[33,36] The heterogeneity of clinical indications, use of different applications of force, and different surgical designs in human studies made comparison with the experimental studies difficult. Two studies on dogs used the same design to distract the periodontal ligament, but in one it was done in the maxilla and in the other, the mandible, with more favourable results in the mandible.[22,30] Besides the anatomical differences between the jaws, the breed of dog may also be a confounding factor. Cohen et al. used foxhounds, and this might have contributed to the slower movement of teeth in the maxilla because they have thicker cortical bone than beagles, which were used in the other experiments.[29,30]

The results of the studies on distraction of the periodontal ligament showed that the movement of teeth was slower than that reported in studies on humans, and can probably be explained by the thicker cortical bone in dogs, or the differences in the anatomy of the roots (multi-rooted premolars in dogs compared with human canines).[8] A dog study that directly compared dentoalveolar distraction with distraction of the periodontal ligament showed a higher rate of tooth movement with dentoalveolar distraction, which is similar to the results of clinical research.[30]

Rate of tooth movement

Although both corticotomy and distraction temporarily improved the movement of teeth, measurements of movement varied between individuals in most studies. This could be because orthodontic movement of teeth can be divided into 4 phases: initial, lag, post-lag, and continuous linear phases. The post-lag phase corresponds to the acceleration of movement.[43] Even with standardised, constant, and equal forces, there were large individual differences in the rate of movement and substantial variations among and within individual animals.[44] In contrast, other studies that used substantially different regimens of force reported similar rates of movement among or within individual animals.[45–47] These differences in movement are possibly related to individual variations in the structure and cellular activity of the periodontal ligament and alveolar bone, or to localised differences in the expression of cytokines and growth factors.[45,48]

Another factor that might have affected the rate of movement is the different response of maxillary and mandibular bone to orthodontic forces,[49] but there is no consensus on whether optimal magnitude of force, or metabolic activity and cellular processes are responsible for the different rates.[50] Finally, different methods of measurement such as intraoral calipers and radiography were used.[22,28,30,33] Sanjideh et al. used both and reported that displacement measured with calipers was consistently larger, which indicates that measurements done in this way might not be accurate.[28] Detection bias may therefore be an issue in the interpretation of such measurements.

Biological mechanism of surgically-facilitated movement of teeth

The rate of remodelling in the periodontal ligament is generally considered to be the limiting factor in the biological process involved in the movement of teeth. Hyalinisation is associated with an arrest of movement, so treatment could be more efficient if it is limited.[43,45,46] Some studies in our review described earlier movement of teeth after corticotomy. Bone resorbed more directly after forces were applied without the lag phase, which is typically seen in the normal movement of teeth,[18,20,33] and the absence of this phase could indicate less or faster elimination of hyalinisation, or both.[18,20] These results suggest that operation may increase bony turnover at an early stage, and this could be the mechanism that underlies the acceleration in movement. This is in accordance with results on the velocity of tooth movement, and suggests that movement simultaneously increases as bony turnover increases soon after operation. In 2 studies on rats, Wang et al. and Lee et al. proposed different histological mechanisms for osteotomy distraction and corticotomy. With tooth-borne osteotomy distraction, bone remodelled exclusively at the distraction gap and did not seem to be associated with movement of the root, but in contrast, bone resorbed around the roots after corticotomy.[19,29] This suggests that different surgical techniques may deliver different forces to the alveolar bone, and possibly result in the engagement of different mechanisms and amounts of movement.

In 2 studies, corticotomy was combined with a technique to improve movement, but in both it reduced the catabolic and anabolic metabolism of bone.[14,31] Biostimulation induced by low-level laser treatment possibly accelerated healing of the alveolar defect at the corticotomy site, and inhibited movement of the teeth.[31] Injection of BMP-2 on the tension side was also counterproductive, presumably because it was transferred to the pressure side, which interfered with the effect of the corticotomy and led to a decrease in movement when compared with corticotomy alone.[14]

Long-term follow-up of surgically-facilitated movement of teeth

Two studies only reported follow-up histological data, one at 3 and the other at 6 months after operation, and they showed that levels of osteclasts and osteblasts returned to baseline values.[32,36] Baloul et al. observed that bone homeostasis was restored to baseline levels 7 weeks after operation.[20] Based on this limited evidence, the duration of altered bone structure and rapid movement of teeth is undefined and needs additional investigation, and because of the lack of follow-up data, the long-term effectiveness of accelerated movement after operation is still unclear. It is therefore difficult to establish whether the overall reduction in treatment time would outweigh the potential discomfort for the patient and the costs of the operation.

Complications

Complications were described only in dog studies (Table 5), and most of them reported minimal or no root resorption after surgically facilitated movement of teeth. Iino et al. reported no root resorption in the corticotomy group, but roots resorbed around the area of hyalinisation in the control group.[18] This might have been caused by the elimination of cortical resistance and an increase in bony remodelling, resulting in less hyalinisation, which has been shown to correspond to the extent of root resorption.[51,52] Based on the findings of experimental studies so far, it is not yet possible to reach a conclusion about which surgical technique produces the most desirable effect with the fewest complications.

Conclusions

Current published experimental studies show that operations such as corticotomy and distraction can speed up the movement of teeth. The peak velocity of movement was always at an early stage, and ranged from 2 to 3 week after operation.

In line with the improved velocity of movement, histological or immunohistochemical data, or both, have shown regional increases in catabolic and anabolic remodelling. The peak expression of biomarkers of periodontal remodelling, which was seen at an early stage after operation for all surgical techniques, suggests temporary acceleration and indicates the importance of direct activation of appliances for maximum benefit.

Although complications (severe root resorption or periodontal problems) were not reported in any of the studies, they were often not considered.

Although no conclusion could be drawn about which surgical technique produces the most desirable effect, a number of animal studies on minimally invasive designs (piezopuncture, corticision) showed similar acceleration of tooth movement and limited tissue damage, which might, in future have a broad clinical application. Further studies are needed on the long-term effects of surgically facilitated movement of teeth.

Conflict of interest

We have no conflicts of interest.

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