Skeletal Anchorage in Orthodontics—A Review of Various Systems in Animal and Human Studies

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Purpose: *The aim of the present investigation was to review and evaluate the current literature on skeletal bone anchorage in orthodontics with regard to success rates of the various systems.* ***Materials and Methods:*** *MEDLINE, PubMed, and Cochrane searches (period January 1966 to January 2006, English language) of animal and human studies using skeletal anchorage during orthodontic treatment were scrutinized. A total of 50 relevant articles were identified which investigated various types of implants.* ***Results:*** *Two types of anchorage systems are used in orthodontics:* (1) *osseointegrated dental implants, including temporary mid-palatal implants. These systems were associated with a wide variety of success rates in animal studies. In human studies, the systems were shown to be reliable, with success rates between 85% and 100% (ie, systems still functioning at the end of the orthodontic treatment).* (2) *Nonosseointegrated mini-plates and mini-screw anchorage systems. Titanium mini-plates were associated with 100% success in animals, and hardly any loss of these mini-plates (bone anchors) were lost due to infection in human studies, with success rates between 91% and 100%. Few long-term studies on nonosseointegrated mini-screws were found, but in animal studies, success rates ranged from 90% to 100%. A success rate of more than 75% in human studies is considered favorable for these orthodontic implants, which confirms the clinical applicability of this type of immediate loading anchor support in orthodontics.* ***Conclusions:*** *Both animal and human studies revealed that mesiodistal and intrusion movements can be reliably carried out by means of skeletal anchorage devices. A drawback is that animal studies do not reflect the real orthodontic clinical situation; thus, the outcome of these studies should be interpreted with caution. Human studies, however, show that orthodontic forces between 100 and 400 grams can be applied successfully to skeletal anchorage devices. Appropriate treatment strategies need to be confirmed by randomized prospective clinical trials.* (More than 50 references.) Int J Oral Maxillofac Implants 2008;23:75–88

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The growing demand for orthodontic treatment methods that require minimal compliance and provide maximal anchorage control has led to the expansion of the use of implants in orthodontics.[1–3] Distalization and intrusion of molars during orthodontic treatment is often necessary, and it is not always easy or even possible to perform these tooth movements with conventional techniques. Adequate anchorage control is fundamental for successful orthodontic treatment with fixed appliances and is one of the most important biomechanical issues to consider during treatment.[4] Numerous anchorage techniques for distalization or intrusion have been described in the orthodontic literature; varying degrees of clinical success have been reported.[5–10] Most of these techniques, however, rely on the patient to use extraoral or intraoral mechanics correctly. Skeletal anchorage with a range of titanium plates, screws, and osseointegrated devices might provide a possible solution to this problem.

Skeletal anchorage in orthodontics has developed from the use of dental implants, which are now routinely used for complex dental restorations. This review focuses on osseointegrated anchors (ie, mid-palatal implants, bone anchors, and mini-screws) and reviews the current literature (animal and human studies) on skeletal anchorage, with a focus on the success rates of the various systems.

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LITERATURE REVIEW

A literature search was carried out to identify animal and human studies published from January 1966 to January 2006 concerned with indications, applications, and success rates of skeletal anchorage used to support orthodontic treatment. MEDLINE, PubMed, and Cochrane Library searches were completed in English, together with a manual search to locate relevant literature based on references cited in the various articles. The following search terms were used: orthodontic treatment, tooth movement, dental implants, skeletal anchorage, mini-screws, micro-screws, micro-implants, mid-palatal implants, mini-plates, zygoma-anchor, and bone anchors. Case studies of fewer than 7 cases and publications presented in abstract form were not included.

A total of 49 relevant articles were identified. Among them were 20 articles on animal studies and 6 on human studies using osseointegrated implants in orthodontic treatment. In addition, 13 studies on mini-screws (4 animal studies and 9 human studies) and 10 human studies on mini-plates also fulfilled the inclusion criteria.

Success Criteria

With respect to a dental implant that supports a restoration, *success* can be defined as lack of clinical mobility, infection, pain, foreign body sensation, and dysesthesia. There should be no radiolucency or pocket formation (no probing depth > 6 mm and no bleeding) around the implant.[11,12] Twelve months from the initial placement, average marginal bone loss should be less than 1.5 mm, and thereafter, annual bone loss should be less than 0.2 mm.[13,14] The definition of *success* varied greatly between articles, which makes comparison of different studies difficult.[15]

As a minimum requirement, orthodontic skeletal anchorage devices must remain stable during periods of loading to be considered successful. In comparison, osseointegrated dental implants, which serve as long-term support for prostheses, can only be considered successful if they remain in place for many years. Because of marked differences between these forms of skeletal anchors, some studies merely report "survival" rates. In the present investigation, survival rates were not used, but cumulative success rates are reported when these result from similarly defined success criteria.

In the case of temporary orthodontic anchorage devices (ie, mid-palatal implants, mini-plates, and mini-screws), Cheng et al[16] suggest that absence of inflammation, absence of clinically detectable mobility, and the capacity to sustain loading throughout the course of orthodontic treatment be considered essential for success. As a result of the present investigation, our research team modified this definition for temporary skeletal anchorage devices. Orthodontic anchorage devices were considered successful if

- They were adequate in function under orthodontic traction throughout the orthodontic treatment period
- They were not associated with any discomfort or pain
- There was an absence of
  - Clinically detectable mobility
  - Infection of the mucosa and bone
  - Damage to the roots of neighboring teeth
  - Paresthesia or penetration in the mandibular canal, maxillary sinus, or nasal cavity

OSSEOINTEGRATED IMPLANTS

Orthodontic anchorage can be achieved with the use of osseointegrated dental implants, either placed as part of restorative dentistry requirements or used solely as a temporary device for orthodontic anchorage, without negative reciprocal influences on tooth position. These implants may be useful in orthodontics when molars are absent, when extraoral devices are impractical, or when noncompliance during treatment is likely.[1] A precondition for successful osseointegration is that sufficient bone is available in the alveolar crest, the retromolar area, or the midline of the palate. Implants placed in the alveolar crest are used mainly for prosthodontic rehabilitation, but they can play a role in supporting orthodontic tooth movement, while implants placed in the palate and retromolar area are used only for orthodontic anchorage.[17–19] Although no significant complications have been reported for implants placed in the palate or retromolar area, removal of such implants requires a surgical procedure at the end of orthodontic treatment.

Animal Studies

In Table 1, animal studies in which endosseous titanium implants were used as an anchorage unit are reviewed. The implants were placed in the alveolar crest of the maxilla and mandible. Different types of animals were used,[20–23] and in the earliest investigations, the implants had low success rates.[20,24]

The success rates of the Bioglass-coated implants, Vitallium implants, and acid-etched titanium implants were high (93.8% to 100%).[19,21,22,25,31,37,38] Fritz et al,[39] in a study in dogs, reported a loss of 4 implants during the healing time, but possible causes were not discussed.

Forces from 60 to 200 grams were associated with high success rates, with loading times varying from 4 to 52 weeks.[21,22,24–31,40,41] Heavy forces of 600 grams were used to protract the whole complex of facial bones with equally good success.[41] The orthodontic movements carried out were mesiodistal movements,[20,23,24,26,29–31,37–40,42,52] intrusion of molars,[28,30] and traction between pairs of implants.[21,25] Vitallium implants remained stable, whereas Bioglass implants showed rotation and mobility, caused by the development of a connective tissue layer. Bioglass implants are no longer used because of this disadvantage. Restricted transverse growth was observed in dogs in the canine region after insertion of a mid-palatal implant. These results may be of some clinical relevance when implants are to be inserted for orthodontic anchorage in growing individuals.[44]

Human Studies

Retromolar Implants. Protraction or retraction of the maxillary or mandibular dentition was successfully carried out in a clinical trial by Higuchi and Slack[45] using forces from 150 to 400 g (Table 2), but loosening abutment screws and surgical access limitations in the ramus region complicated the treatment. Trisi et al[46] successfully distalized mandibular molars, and all implants remained stable during orthodontic treatment and were removed afterward.

Mid-palatal. Osseointegrated mid-palatal implants are designed for anchorage control in the maxilla. The thickness of the anterior mid-palatal bone allows placement of the implant, which can be connected to the first premolars or molars by a palatal bar to prevent loss of anchorage. The mid-sagittal area of the palate proved to be a reliable site for placement using implants with a length of 4 to 6 mm and a diameter of 3.3 mm.[47]

The results of a clinical study suggested that the vertical bone support in this region is at least 2 mm higher than is apparent from a lateral cephalogram.[48] Conversely, an in vitro study by Henriksen et al[49] on dry skulls showed that 4 mm mid-palatal implants can be used safely, but that 6 mm implants should be used with caution. Furthermore, they found that cephalograms should be interpreted cautiously. The clinical results of similar trials by Gahleitner et al[50] also supported these results. Moreover, Tosun et al[51] recommended the use of a template to assist accurate placement and positioning.

A less invasive alternative to osseointegrated implants in the palate is a subperiosteal palatal anchor (Onplant). This anchor was developed using a titanium disk with a hydroxyapatite surface. This subperiosteal device becomes biointegrated onto the surface of the bone.[52] Onplants have been shown in animal models to provide sufficient anchorage to move and anchor teeth. This application has not been widely accepted because clinical assessment of integration is difficult. Another alternative, developed by Glatzmaier et al,[53] was the use of biodegradable implants (length of 6 mm, polylactide alpha-polyester), connected to a titanium abutment. In vitro, these biodegradable implants appeared to have capabilities similar to those of orthodontic anchors. Such implants could be used without the need for surgical removal. However, no clinical studies have been published to date to evaluate the clinical practicability and biocompatibility.

Most clinical and radiological studies of mid-palatal implants with 3 months of healing time and 12 months of treatment revealed no implant mobility or loss (Table 2). Favorable peri-implant soft tissue conditions were noted,[19,51] and no marked movement of the implant-supported anchor teeth was observed. Bernhart et al[54] observed loss of some palatal implants with orthodontic loading up to 8 N; they reported a success rate of 84.4%.

MECHANICALLY RETAINED ANCHORS: MINI-PLATES

Recently a number of animal and human studies have been published on the use of mini-plates fixed with micro-screws for orthodontic purposes. Skeletal anchorage systems,[33,55] zygoma anchorage systems (ZAS),[34,56] and orthodontic bone anchorage systems have been tested.[57] These applications have been developed from the mini-plates used in facial trauma and reconstructive surgery.[58]

Skeletal anchorage systems or bone anchors consist of bone plates (head, arm, and body components) and fixation screws. Both are made of pure titanium, are biocompatible, and are suitable for temporary osseointegration. The head component is exposed intraorally and can be connected with the arch wires of the fixed appliances. The use of short micro-screws to stabilize mini-plates reduces the danger of injuring neighboring anatomic structures.[55,59]

Animal Studies

In animal studies, titanium mini-plates loaded with 1 to 3 N of force showed success rates of 97% to 100%, but slightly inflamed soft tissue was recorded, and some root resorption was seen because of intrusion (Table 3).[33,34]

Human Studies

Success rates of 85.4% to 100%[16,55–57,59–61,71] have been recorded in human studies (Table 4). Mini-plates

Table 1 Animal Studies—Implants

Study	Study design	Implant system	Implant site	No. of implants (dimensions)	No. of animals	Orthodontic load
Sherman[20]	Pilot	Vitreous carbon implants	Third molar area	6	3 dogs	175 g
Turley[23]	Pilot	Titanium implants (manufacturer not reported)	Alveolar ridge, mandible; lingual mandible; palate; temporal buttress; zygoma	42 (l = 6, w = 4.75)	6 dogs	300 g
Gray[25]	Retrospective	Bioglass-coated Vitallium	Femur (n = 24)	12 12 12 4 4 4	12 rabbits	60 g 120 g 180 g 60 g 120 g 180 g
Roberts[21]	Prospective	Acid-etched titanium implants (manufacturer not reported)	Femur (n = 28)	28 loaded 28 controls (w = 3.2, l = 8)	14 rabbits	100 g
Douglass[24]	Prospective	Ticonium rods	Maxilla	21 (w = 1.5, l = 8)	21 rats	60 g
Smalley[41]	Prospective	Titanium implants Nobelpharma	Maxilla Zygoma Maxilla and zygoma	8 (w = 3.75, l = 5)	1 monkey 1 monkey 2 monkeys	600 g
Roberts[22]	Prospective	Biotes and acid-etched implants	Femur Mandible	16	rabbits dogs	3 N (300 g)
Linder-Aronson[40]	Case control; pilot	Biotes	Mandibular extraction sites	2 (l = 7)	2 monkeys	60 g
Wehrbein[26]	Case control	Brånemark	Mandibular pre-molar sites	8 (4 controls) w = 3.75; l = 10	2 foxhounds	2 N (200 g)
Southard[28]	Prospective	Brånemark	Mandibular pre-molar sites	8	8 dogs	50–100 g
Block[52]		Onplant hydroxy-apatite disk 10 mm wide 2 mm long	Palate Mandibular ramus	8 2	4 monkeys 1 control	121 g
Wehrbein[27]	Prospective	Bonefit	Maxillary alveole and palate	8 (w = 4, l = 6) 2 (w = 4, l = 6)	2 dogs	2 N
Akin-Nergiz[29]	Prospective	Bonefit screw-type	Mandibular pre-molar areas	18 (w = 4.1, l = 12) 6 controls	3 dogs	2 N 5 N 0 N
De Pauw[30]	Prospective	Brånemark	Zygomatic arch	30 (w = 3.75; l = 7, 10, or 15)	5 dogs	Removal torque, axial 5 N
Majzoub[31]	Prospective	Titanium implants (manufacturer not reported)	Calvarial midsagit-tal suture	20 (w = 4; l = 3.25) 4 controls	10 rabbits	150 g 0 g
Saito[42]	Prospective	Brånemark	Mandibular sec-ond or third molar areas	16 (w = 3.75, l = 7)	4 dogs	200 g
Gedrange[75]	Retrospective	Disks, diameter 3 to 5 mm	Palate (medial and paramedial)	103	75 pigs	Average 47 ± 5 N for new-born animals, 54 ± 4N for juveniles, 45 ± 2 N for adults
Fritz[39]	Prospective	Straumann Orthosys-tem SLA	Maxilla and mandible	16 (w = 3.3, l = 4) 1 control	4 foxhounds	50 cN (extrusive) 200 cN (translatory)
Aldikaçti[37]	Clinical, radiologic, histologic	Straumann SLA implants	Maxilla Mandible	2 (1 control; w = 4.1, l = 10) 4 (1 control)	3 dogs 5 dogs	2 N (200 g)
Oyonarte[38]	Clinical, histo-morphometric	Porous titanium Threaded titanium (Innova)	Mandible	15 (w = 5, l = 5) 15 (w = 5, l = 5)	5 dogs	100 to > 300 g

Information on manufacturers: Vitallium (Dentsply Austenal, York, PA); Ticonium (Albany, NY); Biotes (Nobel Pharma, Göteborg, Sweden); Brånemark (Nobel Biocare, Göteborg, Sweden); Onplant (designed by Block, Louisiana State University), Bonefit (Straumann, Basel, Switzerland); Orthosystem (Straumann).
l = length, w = width (diameter); measurements shown in mm.

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
—	—	Mesiodistal	Mobility; implant fracture	33.3%	Mobility; implant fracture
7–9 wk	20 wk	Mesiodistal	Anatomic placement: lingual mandible, zygoma; not loaded; early loading and insertion in nonkeratinized gingiva	57%	Mobility; soft tissue inflammation
4 wk	4 wk	Traction between pairs of implants	Mobility	94.4% 100%	Mobility
4–8 wk	6–12 wk	Traction between pairs of implants	Mobility	95%	Mobility; fracture of the femur
4 wk	8 wk	First molar movement	Death; lack of stability	23.8%	Mobility
12 wk 12 wk 18 wk	13–15 wk	Extraoral orthopedic traction; protraction	—	100%	Differences in response; relapse of skeletal movement; mild inflammation
20 wk				15/16 (93.8%) clinically rigid after 13 wk	Only 10% bone contact
8 wk	2 mo	Mesiodistal, contralateral	—	100%	Gingivitis
26 wk	25 wk	Distalization	—	100%	Mild gingivitis
16 wk	3 mo	Intrusion	—	100%	—
5 mo	12 wk	Distalization	Infection	75%	Infection; soft tissue dehiscence
26 wk	8 wk	Not reported	—	100%	Needs 59 kg shear force
12 wk 24 wk total of 36 wk	12 wk	Mesialization	—	100%	Implants loaded by masticatory forces showed significantly smaller probing depth (1.5 mm) than unloaded ones
8 wk	8 wk	Horizontal displacement	—	100%	—
8 wk	2 wk	Distalization	Mobility	95%	—
32 wk	18 wk	Distalization	—	100%	Mild hemorrhage
Not reported	Not reported	1-point stress and 2-point stress	—	Not reported	Bone fracture
Not reported	6 mo	Intrusion Distalization	4 lost spontaneously during healing period	73.3%	More distinct osteodynamic activity in extrusively loaded implants
52 wk	6 wk	Horizontal	—	100%	Thicker corticalization in loaded implants; gingivitis
22 wk	Not reported	Horizontal	Not reported	96.7%	Porous surface more effective than threaded

Table 2 Human Studies—Dental implants

Study	Study design	Implant system	Implant site	No. of implants	No. of patients	Orthodontic load
Higuchi[45]	Clinical trial	10-mm titanium implant Nobelpharma	Mandibular third molar region Mandibular first molar region	12 2	7	150 to 400 g
Ödman[18]	Prospective	Brånemark titanium implants	Different sites	23	9	Not reported
Wehrbein[19]	Prospective	Orthosystem	Midpalatal	9 (w = 3.3, l = 4 to 6)	9	1.5 to 2 N
Bernhart[54]	Prospective	Epithetic implants	Paramedian region palate	21 (w = 3.75, l = 3 to 4)	21	Up to 8 N
Tosun[51]	Prospective	Frialit-2	Palate	23 (w = 4.5, l = 8)	23	Not reported
Trisi[46]	Prospective	Exacta	Retromolar palate	12	12	80 to 120 g

Information on manufacturers: Brånemark (Nobel Biocare); Orthosystem (Straumann); Frialit-2 (Dentsply Friadent Ceramed, Lakewood, CO); Exacta (Ormco, La Spezia, Italy).
l = length, w = width (diameter); measurements shown in mm.

Table 3 Animal Studies—Mini-plates

Study	Study design	Implant system	Implant site	No. of implants	No. of animals	Orthodontic load
Daimaruya[33]	Pilot case study	Titanium mini-plates (SAS)	Mandible	5 5	6 dogs	100–150 g
Daimaruya[34]	Pilot case study	Titanium mini-plates (SAS)	Maxilla	5 5	6 dogs	100–150 g

provided stable anchorage for orthodontic tooth movement, particularly for distalization of teeth in the mandible,[55] protrusion and tipping of teeth,[57] and intrusion of molars in the maxilla.[16,56,61] However, peri-implant tissue inflammation was recorded,[16,56,57] and subperiosteal bone apposition was seen.[59] The zygomatic area was also shown to be a useful anchorage site.[56,62]

MECHANICALLY RETAINED ANCHORS: MINI-SCREWS

Small titanium screws have been used as a means of temporary orthodontic anchorage using mechanical monocortical bone retention.[63] Several extra-alveolar regions, including the incisive fossa, canine fossa, infrazygomatic ridge, premaxillary region, and mid-palatal region in the maxilla and the mandibular symphysis, canine fossa, retromolar area, anterior external oblique ridge, and submaxillary fossa in the mandible are all suitable for placement of these temporary anchorage devices, with lengths ranging from 4 to 12 mm. In general, titanium screws of 4 to 6 mm in length are safe in most of these anatomic sites.[63]

Titanium mini-screw systems of various designs and lengths have been developed to be used as orthodontic anchors to minimize the surgical trauma and related damage to adjacent structures caused by mid-palatal and mini-plate anchors. The mini-screws used for fixation of bone plates served as the starting point for this novel approach to anchorage.[35,54,64–66]

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
3 y	4 to 6 mo	Protraction of mandibular and maxillary dentition; retraction	—	100%	Loosening abutment screws; surgical access limitations in ramus region
32 mo 17 mo avg treatment	3 to 9 mo	Tipping, torquing, rotation, intrusion, extrusion, bodily movement	—	100%	Loosening brackets on implant crowns
11 mo ± 3 wk	3 mo	Retraction anterior teeth	—	100%	Slight mucosal inflammation
22.9 mo	4 mo	Mesiodistal traction; direct and indirect loading	3 lost during loading	84.8% time related	Peri-implant inflammation after loading
Duration of the orthodontic treatment	3 mo	Maxillary molar distalization	—	100%	Slight plaque accumulation
2 to 12 mo	2 mo	Distalization	—	100%	Microcracks and microcalli; increased remodeling rate

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
4 mo 7 mo	3 mo	Molar intrusion	—	100%	Slightly inflamed soft tissue
4 mo 7 mo	3 mo	Molar intrusion	—	100%	Root resorption; apices penetrated into the nasal cavity

Mini-screws are stable but, unlike endosseous implants, they do not remain absolutely stationary throughout orthodontic loading.[67] Initial clinical experiences are promising, however. Potential advantages of such systems are simple, atraumatic insertion and removal; increased patient comfort; and a favorable cost-benefit ratio.

Animal Studies

Table 5 summarizes the results of clinical and histologic evaluations of titanium mini-screws (1 mm diameter and 4 to 10 mm in length) in animals. Experiments in dogs demonstrated that mini-screws loaded after a short healing period are effective tools for intrusion and mesiodistal tooth movements.[35,36] None of the loaded mini-screws showed any displacement. In addition, loaded mini-screws showed more active bone remodeling than controls with nonloaded mini-screws. Partial growth of bone into the screw threads was seen, but osseointegration had not taken place. Thus, the implants were sufficiently anchored for orthodontic purposes but could still be removed manually.

Success rates varied from 87.5 %[32] to 100%.[35] Loss of the mini-screws was associated with inflammation around the implant site and surgical access problems in the posterior parts of the mandible. Melsen and Costa[32] concluded that immediately loaded screws are able to function well as an intraoral extradental anchorage system for tooth movements that cannot be carried out with conventional anchorage. The results of a minipig study carried out by Büchter et al[68] further confirmed that mini-screws can be imme-

Table 4 Human Studies—Mini-plates

Study	Study design	Implant system	Implant site	No. of implants	No. of patients	Orthodontic load
Miyawaki[60]	Retrospective clinical study	Mini-screws (Manufacturer not reported) Mini-plates	Zygoma and buccal mandible			
Cheng[16]	Prospective clinical study	Mini-screws Leibinger/Monsteal Mini-plates	Posterior maxilla Posterior mandible (and anterior)	140 (92 freestanding, 48 in mini-plates) 34	44	100–200 g
Erverdi[56]	Preliminary study	Mini-plates Leibinger 2	Zygomatic buttress	20	10	Not reported
Sugawara[55]	Retrospective	Mini-plates	Distal to mandibular second molars	29	15	Not reported
Ari-Demirkaya[61]	Prospective	Mini-plates; Manufacturer not reported	Zygomatic buttress	32	16	Not reported
Londa[59]	Clinical	Mini-plates (Medican)	12/13, 33/34, 43/44 (FDI tooth numbers)	11 (w = 1.5, l = 4)	10	150–200 g
Mommaerts[57]	Clinical	Mini-plates OBA	Premolar, anterior, retromolar	35	18	150–200 g
Yao[73]	Retrospective	Mini-screws, mini-plates (Leibinger/ Monsteal)	Buccal and palatal	18 mini-plates	22	150–200 g

Leibinger, Freiburg, Germany; Mondeal, Tuttlingen, Germany; Leibinger2, Mühlheim, Germany; Medicon, Tuttlingen, Germany; OBA (orthobone anchor), developed by Mommaerts. l = length, w = width (diameter); measurements shown in mm.

Table 5 Animal Studies—Mini-screws

Study	Study design	Implant system	Implant site	No. of implants	No. of animals	Orthodontic load
Melsen[32]	Prospective	Mini-screws Arhus	Symphysis Infrazygomatic crest	8 (l = 8) 8 (l = 8)	4 monkeys	25–50 g
Ohmae[35]	Clinical and histologic study	Mini-screws Sankin	Mandibular third premolar region	12 (w = 1.0, l = 4) 24 control (w = 1.0, l = 4)	3 dogs	150 g
Deguchi[36]	Prospective	Mini-screws Stryker Leibinger	Maxilla and mandible	96	8 dogs	200–300 g
Büchter[68]		Mini-screws Absoanchor Dual tap	Mandible, closed flap technique	102 (w = 1.1, l = 10) 98 (w = 1.6, l = 10.0)	8 minipigs	100 g 300 g 500 g

Arhus (Medident, Hellerup, Denmark); Sankin, Tokyo, Japan; Stryker Leibinger, Kalamazoo, MI; Absoanchor (Dentos, Taegu, Korea); Dual Top (Jeil, Seoul, Korea) l = length, w = width (diameter); measurements shown in mm.

diately loaded by continuous forces not exceeding a tipping-moment (force × lever arm) of 9 N-mm. This study showed good success rates, but the conditions of the experiment differed from routine clinical procedures.[68]

Human Studies

Various types of mini-screws have been used in humans in different anatomic sites and with various loads (Table 6). Some general trends have been observed. Success rates have ranged from 70% to 100%.

Mini-screws used in the mid-palatal area remained very stable during orthodontic loading.[69] Varying orthodontic forces from 100 to 400 g were used, and no differences in success rate related to the amount of force were found. In addition, small-diameter mini-screws (1.0 mm) are apparently more prone to failure than screws with a diameter of 1.5 to 2.3 mm.[60,70] Immediate loading was not applied in all studies, although there are strong indications that immediate loading of mini-screws of 2 mm in diameter is possible.[64] The preferred insertion locations are the interradicular site, the buccal and palatal sides in

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
12 mo	Not exactly reported	Variable	Inflammation; high mandibular plane	96.4%	Inflammation
Up to 140 wk Up to 80 wk	2-4 wk	2/3 molar intrusion or uprighting 1/3 retraction anterior teeth	Nonkeratinized mucosa	cumulative success rate 89%; plates, 85.4%	Peri-implant infection, mobility
Not reported		Intrusion maxillary molars	None	100%	Tissue inflammation
1 y	Immediate	Distalization mandibular molars	None	100%	Average of 0.3 mm relapse
Not reported	Immediate	Intrusion maxillary molars	None	100%	Clinically insignificant root resorption
Not reported	2–3 wk	Mesialization	None	100%	Subperiosteal bone apposition
up to 30 mo	2–3 wk	Horizontal Vertical in the anterior region	Inflammation in retromolar area	91.4%	Tissue inflammation; mastication trauma
5-12 mo, mean 7.6	1–2 wk	Intrusion maxillary molars	Not reported	No loss reported	Not reported

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
Not reported	Immediate	Extrusive and horizontal forces	Difficulties in surgery mandible	87.5%	Inflammation of the mucosa
12–18 wk	6 wk	Intrusion	None	100%	More remodeling due to loading; mild root resorption
3 mo	3 wk	Intrusion Mesiodistal movement	3 screws lost during healing period	97%	All failures in the mandible; surgical problems
22 d or 70 d	Immediate	Transverse	None		Bending of 4 screws (w = 1.1 mm, l = 10.0 mm)

the posterior region of the maxilla and mandible, and the zygomatic crest. In some studies, mini-screws were studied as free-standing devices; in others, they were used as anchors for mini-plates. The success rates of mini-plates with 2 screws were approximately 10% higher than the success rates of free-standing mini-screws; however, this difference was not statistically significant.[60]

Orthodontic indications, anchor type, screw system used, length of mini-screws, and oral hygiene status did not significantly correlate with the occurrence of peri-screw infection. However, screws in the posterior mandible and those surrounded by nonkeratinized mucosa were prone to failure.[16] In 1 study, bicortical screws were used.[65] However, the clinical implications of this bicortical approach are questionable, especially because a computerized tomographic scan is required for this technique.[65]

Displacement of mini-screws as a result of orthodontic forces is a problem because adjacent structures can be damaged. To minimize this risk, a clearance of 2.0 mm between the mini-screw and the dental root or other vital structures (eg, nerves, blood vessels) is recommended.[67]

Table 6 Human Studies—Mini-screws

Study	Study design	Implant system	Implant site	No. of implants	No. of patients	Orthodontic load
Costa[64]	Clinical trial	Cizeta mini-screws	Inter-radicular; zygomatic crest; palate; anterior nasal spine	16	14	Not reported; Nitinol coilsprings
Freudenthaler[65]	Case series	Bicortical mini-screws	Between roots, premolars, and canines	12 (w = 2.0; l = 13)	8	150 g
Miyawaki[60]	Retrospective clinical study	Mini-screws Manufacturer not reported Mini-plates; Manufacturer not reported	Molar region (maxilla and mandible)	10 (w = 1.0; l = 6) 101 (w = 1.5, l = 11) 23 (w = 2.3, l = 4)	3 31 10	2 N
Cheng[16]	Prospective clinical study	Mini-screws Leibinger/Mondeal Mini-plates Leibinger/Mondeal	Posterior maxilla	140 (92 free-standing, 48 in mini-plates) 34	44	100–200 g
Liou[67]	Prospective clinical study	Leibinger mini-screws	Zygomatic butress	32 (w = 2.0; l = 17)	16	400 g
Fritz[70]	Clinical trial	Jeil mini-screws	Palate, buccal mandible, retromolar area	w = 1.4, 1.6, or 2 l = 6, 8, or 10 36 total	17	Not reported
Gelgör[69]	Prospective	IMF Stryker-Leibinger mini-screws	Palate	25 (w = 1.8, l = 8 or 14)	25	250 g per side
Yao[73]	Retrospective	Mini-screws mini-plates Leibinger	Buccal and palatal	26 mini-screws (w = 2.0, l = 15)	22	150–200 g
Park[74]	Prospective	Mini-screws 2 Martin, 22 Osteomed, 6 Dentos	22 distal mandibular sites; 8 buccal maxillary sites between premolar and molar	30 (w = 1.2, l = 6)	13	200 g

Cizeta Surgical, Bologna, Italy; Leibinger, Freiburg, Germany; Jeil Medical, South Korea; IMF Stryker-Leibinge, Freiburg, Germany; Mondeal, Tuttlingen, Germany; Martin, Kalamazoo, MI; Osteomed, Dallas, TX; Dentos, Daegu, Korea. l = length, w = width (diameter); measurements shown in mm.

Causes of failure of mini-screws during orthodontic treatment are somewhat unclear. Such failures have been attributed to torsional stress, heavy smoking, and insertion of the screw at the interface between attached and nonattached gingiva. Mucosal proliferation over the screw head and inflammatory irritation have also been reported.[16,60,64,65,69,70] Local irritation is generally limited and can be controlled by local application of chlorhexidine.[64,65,69] A high mandibular plane angle was also a risk factor for mobility of screws, which may be due to anchorage in thinner cortical bone.[60] Spontaneous loss of mini-screws before orthodontic loading has also been reported.[64] Overall success depends on bone quality, and the patient should be instructed to maintain a high level of oral hygiene and avoid toothbrush trauma and habitual contact with the screws.

A general conclusion is that comparing different types of mini-screws with varying diameter and lengths in various anatomic sites is difficult because of the number of variables. However, with success rates of 70% to 100%, the clinical application of this type of anchorage system is acceptable.

HISTOLOGIC AND MORPHOMETRIC ANALYSES OF IMPLANT SITE

In animal studies, histologic and microradiographic examination after 8 weeks of force application showed the formation of normal connective tissue without an inflammatory reaction.[40] Regarding osseointegration, no significant differences could be found between the pressure and tension sides of an implant after loading, whereas the unloaded control implant showed less bone-to-metal contact length.[26,27,31,37] However, these results are in contrast with the outcomes of another study on osseointegrated implants, where bone remodeling was significantly more pronounced at the tension side, irrespective of implant length.[30]

Histomorphometric analysis showed more distinct osteodynamic activity with extrusive loading than with translatory loading, which showed increased appositional activity.[39] Corticalization of bone trabeculae around the loaded implants was more pronounced than around the unloaded implants, and new bone formation at the level of the crest was

Follow-up period	Start of loading	Movement	Causes of loss	Success rate	Complications/ notes
Not reported	Immediate	Retraction; protraction; intrusion	2 spontaneously; 1 after 2 mo loading	81.3%	Covering of the screwhead by nonattached mucosa
12 mo	Immediate	Protraction molars	Soft tissue problems	75%	Slight inflammatory reaction
12 mo	Not clearly stated	Variable movements	Inflammation; high mandibular plane	0% 83.9% 85%	Inflammation
up to 140 wk up to 80 wk	2–4 wk	Two-thirds molar intrusion or uprighting One-third retraction of anterior teeth	Nonkeratinized mucosa	Cumulative, 89%; screws, 91.3%	Peri-implant infection, mobility
9 mo	2 wk	Retraction anterior teeth	—	100%	Displacement of screws (not clinically significant)
Min 17 d, Max 425 d	0–4 wk	Variable movements	Not reported	70%	Tissue proliferation, coverage of the screwhead
3–6.2 mo mean 4.6 mo	Immediate	Distalization maxillary molars	—	100%	Minimal inflammation
5–12 mo mean 7.6 mo	1–2 wk	Intrusion maxillary molars	Not reported	100%	Not reported
12.3 ± 5.7 mo	Not reported	Distalization molars	Not reported	90%	Soft tissue inflammation and overgrowth of soft tissue over second molars

slightly superior in the test implants.[37] Sintered porous implant surfaces may be more successful for orthodontic applications than machine-threaded surfaces due to significantly higher marginal bone levels and greater bone-implant contact.[38]

Histomorphometric data on mini-screws revealed that mandibular mini-screws had significantly higher bone-implant contact than maxillary ones.[36] The calcification of peri-implant bone on loaded implants was either equal to or slightly greater than unloaded controls.[35] Growth of bone into the screw threads increased with time (10% to 58%)[32] independent of bone type and the force level applied. Kim et al[71] found less mobility and more bone-metal contact for mini-screws placed without pilot drilling; however, osseointegration, to a greater or lesser extent, was observed with both systems.

One clinically relevant point was that root repair after injury from mini-screws was seen in histologic examinations and that almost complete repair of the periodontal structure was observed within 12 weeks following removal of the screw.[72]

CONSIDERATIONS

Skeletal anchorage is a valuable option in orthodontics, particularly for the cases requiring intrusions and mesiodistal movements of teeth. The current literature covers many variables that can affect success: the anatomic site, the orthodontic load applied, and the animal used for the research. These variables make it difficult to draw straightforward conclusions from animal studies and to extrapolate the data to routine orthodontic clinical practice. Although good implant stability of osseointegrated implants was reported, sound recommendations cannot yet be made.

Most of the studies have in common long healing periods following implant insertion prior to orthodontic loading, although Majzoub et al[31] showed that shorter healing periods were just as successful. Nevertheless, it can be deduced from animal studies that skeletal anchorage is clinically applicable in humans.

Considering osseointegrated dental implants in humans, those positioned in the retromolar area are stable but difficult to access, while those placed in the mid-palatal area show a high success rate. Mini-screws in general failed to reach these high success rates. However, when mini-screws and mini-plates were compared in humans, several authors reported better results with mini-plates. Survival rates of mini-screws with a minimum diameter of 1.5 mm varied from 70% to 100%; success rates of 100% were only achieved with mini-implants in the mid-palatal area. Mini-plates, however, showed success percentages of 85.4% to 100%.[16,55,56,57,59–61] Although mini-plates are more predictable to use, mini-screws are more simple to insert.

A direct comparison of the failure rates of different studies is problematic because of differences in study design, screw design, and insertion technique. Because of the small number of mini-screw studies, a systematic review was not possible. The conclusions from this paper therefore reflect a cautious interpretation.

A possible explanation for the high failure rate of mini-screws may be their use in complex cases with high orthodontic anchorage demands. The increased biomechanical loading of peri-implant bone, as well as the timing of loading, together with microbiological aspects, are all possible explanations and topics for further research.

Future research concerning skeletal anchorage in orthodontic treatment should be focused not only on success rate but also on evaluation of the comfort of the system, the microbiological implications, the acceptance of the patient, and evaluation of orthodontic treatment outcomes.

CONCLUSIONS

The literature survey demonstrated successful clinical outcomes for all types of skeletal anchorage. Both animal and human studies confirmed that mesiodistal and intrusive tooth movements can be carried out with skeletal anchorage devices. The results from animal studies do not reflect the clinical situation; however, human studies have shown that orthodontic forces between 100 and 400 grams can be applied successfully to skeletal anchorage devices to accomplish the required tooth movements. Success rates could be increased if the causes of implant failure were better understood. Randomized prospective clinical trials are required to draw more valid conclusions. These should focus on implant design, placement techniques, biomechanical principles, and patient-centered and treatment outcome evaluations.

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