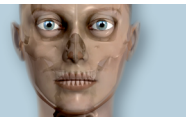
Orthodontics & Craniofacial Research



REVIEW ARTICLE

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Bone anchors – can you hitch up your wagon?

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Abstract The purpose of this review was to address and understand the current status of mini-screw implants (MSI) that are used in orthodontics. Understanding the biologic adaptation of MSI to its adjacent bone is one of the critical factors to their success. The review explores factors that are associated with failure of MSI, with special focus on an understanding of osseointegration as it relates to MSI. The rationale and importance of measuring bone contact and dynamic bone remodeling in animal studies are outlined. The utility of microcomputed tomography (μCT) as a substitute for conventional histomorphometry is debated. Finally, alveolar physiology and rigidity of implants are explored to understand potential reasons for the high failure rate of MSI when compared to endosseous implants.

Key words: bone; histomorphometry; mini-screw; orthodontics; skeletal anchorage

Introduction

We are soon reaching the end of the second decade of using temporary anchorage devices (TAD) in the practice of clinical orthodontics. While these devices were initially used primarily in Korea and Japan, the use of TAD in the USA has remained high (1). The term TAD has gained popularity in the orthodontic literature (2) and refers to a broad group of devices, which includes, for example, mini-screw implants (MSI), palatal implants, and retromolar implants. MSI are clearly the most popular TAD in current use, and the term, MSI, is specifically used to describe small (typically 1.5–2 mm in diameter and 6–10 mm in length) machined devices. Another less popular but possibly a more accurate collective term for these types of devices that are borne by the bone would be skeletal anchors. There is a large vocabulary of terms that have been introduced into the literature to describe these anchorage devices, their design and other

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features associated with their use and a description of such terms can be found in the literature (2).

Mini-screw implants are routinely being used for multiple clinical applications. Anterior en-masse retraction, mandibular molar protraction, maxillary posterior distalization, and maxillary posterior intrusion are few of the clinical applications for which MSI and other TAD can be helpful in providing anchorage (1). However, with many and possibly each of these applications, certain challenges prevail. For example, with maxillary posterior intrusion, the placement of the MSI on the buccal aspect of the posterior maxilla between or apical to the roots of the maxillary first and second molar can be critical. Placement of a miniplate (3) to provide anchorage for maxillary molar intrusion is an alternative, however, involves training of a surgeon and reflection of a flap. These challenges provide for opportunity of developing MSI or TAD with different designs, which may serve similar clinical purposes.

The overall purpose of this critical review was to explore the literature and address important issues that may relate to failure of MSI. In addition, it is imperative to address any deficiencies in research methodology, which detract from making useful translational advances.

Current status of mini-screw implants

Mini-screw implants are placed within the alveolar process typically in an inter-radicular location. As MSI are placed in the close vicinity of the anchorage requirement, they eliminated the need for unnecessarily complex biomechanics and strategies that were typically seen, for example, with retromolar implants (4). This versatility of placement was considered as the major advantage for these anchors.

The literature is replete with numerous case reports and studies on the potential and possibilities of enhancing anchorage with MSI (5). However, one of the major issues with MSI is the persistently high failure rates (6). Orthodontists are also interested in other skeletal anchorage options such as miniplates (7) and other extra-alveolar sites for MSI placement, such as the palate (8). The salient difference between many of these TADs is that MSI currently cannot routinely support larger forces (e.g., 10 N) and over a prolonged duration (1–2 years) and are typically used for movement of few teeth over a period of 6–8 months (5).

One of the assumptions made by researchers and clinicians alike is that MSI would serve in an identical manner to endosseous implants. Endosseous implants were demonstrated beyond doubt to be rigid and were capable of withstanding high orthodontic forces and prolonged loads (9). They osseointegrated to the bone and no movement of implant device was observed (10). While it was desired that MSI would not fully osseointegrate and could be removed upon completion of their use, some of the other sequelae such as high (11) failure rate (10–30%) and displacement (12) were not anticipated.

Osseointegration – what does it mean?

A major challenge for researchers in developing a more successful implant device is to determine how a 'successful' implant appears on histological examination. These histological studies are conducted in animals or from retrieval specimens from humans. The definition and mechanism of a successful implantation historically has been described by the term *osseointegration* (13). Osseointegration is the presence of vital load-bearing bone directly in contact with the implant. The term osseointegration is defined at a tissue level in animals, and thus, most of the implant studies examine bone sections and quantify histological outcome variables that are suggestive of a favorable response at the interface. For example, percent bone to implant contact (%BIC), percent bone volume fraction (% BV/TV) within the threads of an implant, bone remodeling (% bone formation rate/year, %BFR/year) in the implant adjacent bone can be measured. However, there are no clear quantifiable

metrics of what constitutes a successful implant on a histological section. In addition, one cannot evaluate a successful implant solely from a histological section as other mechanical factors (e.g., primary and secondary stability) cannot be measured on histological sections.

In contrast, a failed or failing implant can be ascertained from histological sections (Figs 1 and 2). The presence of fibrous tissue and woven bone (14) instead of load-bearing lamellar bone at the implant interface is indicative of overload and augurs to future failure. Another major challenge in animal studies is the inability to carry out these implant studies to long durations (>9–12 months), thus mimicking their clinical use. While many studies examine the early time points (weeks and months after implantation), longer time points after bone healing has occurred are difficult to conduct in experimental designs and costs can be prohibitive. Finally, selection of an appropriate animal model, interpretation and extrapolation of results to humans has to be attempted with caution (15). Within the framework of implant research, *in vitro* studies have contributed to the understanding of the cellular and molecular responses and gene expression, which may be predictors for the success of various implant surface modifications (16).

Animal studies – what histological variables should be measured?

There are a large number of implant studies conducted in a variety of animal models. Animal models serve as one-step toward translation of discovery to humans, and there are limitations and advantages to each animal model (15). The typical histomorphometric variables that should be measured to provide information to the reader and for preventing repetition of studies especially on larger animal models (17) are discussed below.

Bone contact

Bone to implant contact frequently referred as BIC is measured in most histological studies. The measurement is relatively straightforward but requires an intact bone implant interface with the implant and the bone being sectioned together, which itself is challenging. Bone contact as measured in studies is a static measurement of a dynamic process. The presence of bone remodeling at the implant interface is evidence that bone contact is dynamic. That is, it may increase or decrease and different areas of the implant may contact bone at different times (18). Given that the remodeling rate is elevated and high at implant interface (19), it is likely that bone contact does change.

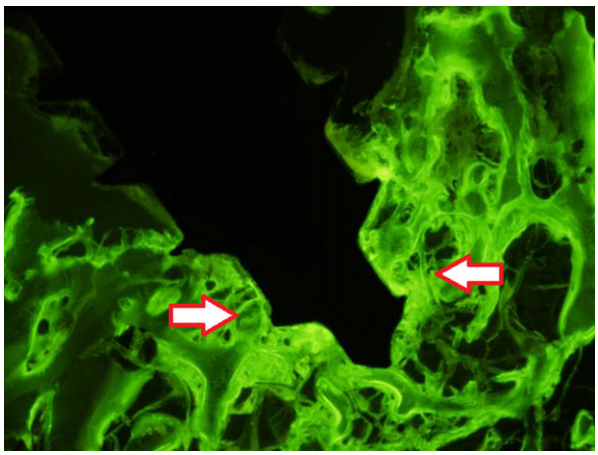

Fig. 1. Epifluroscent micrograph of apex of a 2-mm miniscrew demonstrating diffuse calcein label, which is indicative of woven (arrows) bone formation. Woven bone is either present early on in healing or as in this case suggestive of overload and a failing mini-implant.

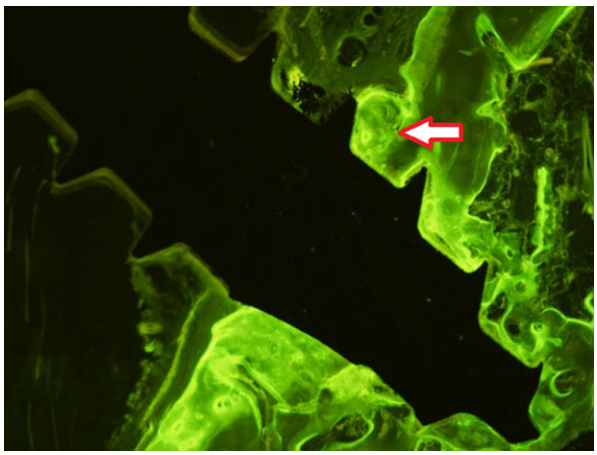

Fig. 2. Epifluroscent micrograph a 2-mm miniscrew demonstrating diffuse calcein label on the left side of the implant within the cortical bone and along the entire interface. Note the periosteal callus (arrow) forming on the right side of implant above the old cortical plate is indicative of need for increased bone stability.

A question that intrigues researchers and clinicians alike is the relationship, if any, between bone contact with implant and implant success. Hematoxylin and eosin sections (20) do not as readily identify load-bearing bone in a manner similar to undecalcified bone containing intravital labels (21). Woven bone or fibrous tissue contact (Figs 3 and 4) is not a sign of successful integration for endosseous implants (14) and MSI but rather indicative of an overload situation and suggestive of impending failure. There is evidence in the literature that the shape of the implant and the design of the implant threads (symmetric, vs. asymmetric) can influence the amount of bone contact (14). However, it is unknown if an implant with 80% of bone contact will fail, while an implant with 30% bone contact will be successful or vice versa. Bone contact alone is not a predictor for implant success. Retrieval analyses of dental implants that were in function for many years, reveal 50–60% bone contact (22). An additional method of measuring the bone at the interface is to examine the bone volume (BV) (23) adjacent to the implant and contained within the threads (Fig. 5). This bone is either generated by contact osteogenesis or distance osteogenesis (23). The rationale here is that bone ingrowth occurs toward an osteogenic (osteoinductive vs. osteoconductive) surface, in areas where bone did not exist before (23).

Bone remodeling

Presence of viable bone is a key to success at an implant interface. One method to measure the metabolic activity at an implant interface is by estimation of bone remodeling in supporting cortical and trabecular compartments. The elevated bone remodeling during initial phases of healing after implant placement can be described by the term regional acceleratory phenomena (RAP) (24). RAP is the acceleration of metabolic activity that is seen during a healing response in hard and soft tissues. Thus, essentially a RAP (24) like healing would be seen in the implant adjacent bone, with elevated bone metabolic activity at the tissue level of examination by histology. Interestingly, by studying retrieval specimens from various animal species (19), it was observed that even after accounting for periods of time for typical bone healing, a persistent elevated remodeling rate is observed in implant adjacent bone in the long term (e.g., 1–2 years out after implantation). This led one group to conclude that an elevated rate of bone

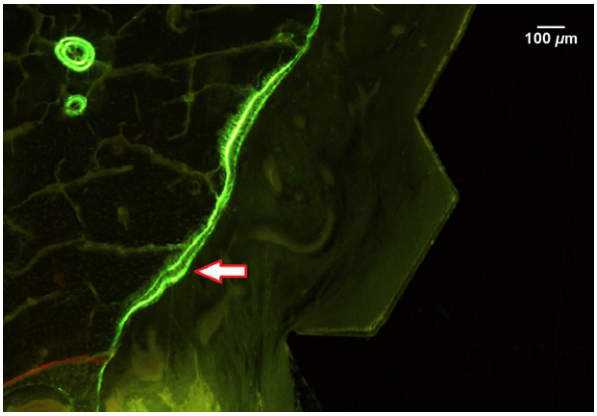

Fig. 4. Failed implant with fibrous tissue interface. Bone is seen on left side and fibrous tissue between the implant and bone.

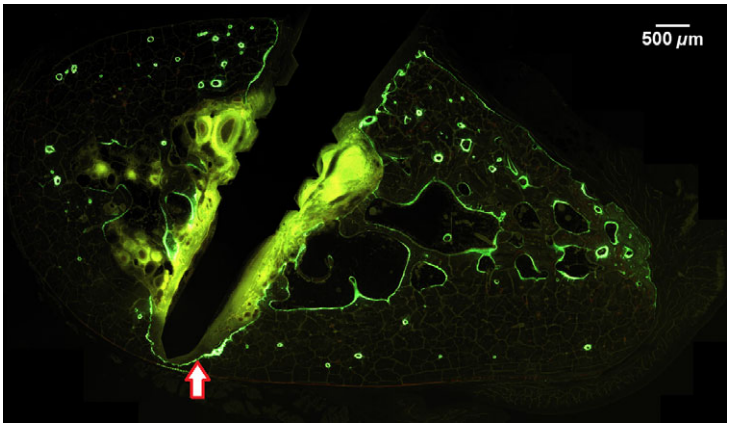

Fig. 3. Failed implant encapsulated with fibrous tissue in a canine model. There is no bone contact, the implant has nearly perforated the opposite cortex (arrow).

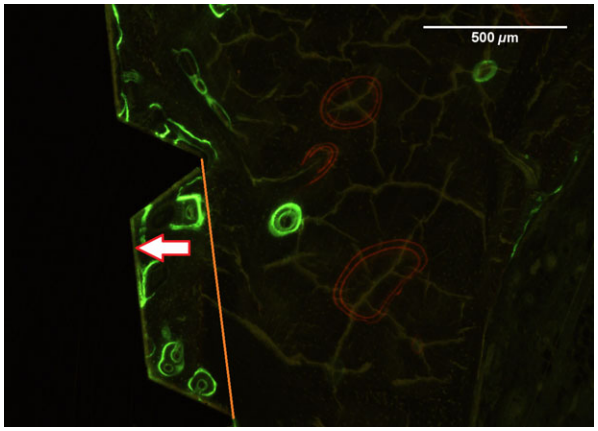

Fig. 5. Vital implant interface. Two bone labels were administered, alizarin (red) and calcein (green) in this animal (canine) model. Calcein label was given 1 week prior to killing the animals. Note bone activity at the implant interface between the threads. The entire bone surface is not in contact with the implant (arrow). These bone labels provide a better measure of vital tissue compared to H/E stained sections. By measuring the bone area from tip of one thread to the other (orange line) one can measure the bone volume supporting the implant.

remodeling in the direct vicinity of the implant (0–1 mm from the interface) was critical to the long-term success of implants (19). However, similar to bone implant contact, it is unclear what the magnitude of the bone turnover should be for it to be beneficial. In other words, can excessive high or low turnover rates, be counterproductive at the implant interface (25)?

Measurement of bone remodeling involves the need to administer intravital bone labels. While many authors use this approach in animal studies, few then measure the histomorphometric variables such as mineral apposition rate, mineralizing surface/bone surface (MS/BS) or bone formation rate (BFR) from the sections. These standardized variables reveal the dynamic nature of the metabolic activity in the bone. Arguably, these dynamic measures reveal more information than static variables such as BIC or BV/TV.

The measurement of both static and dynamic histomorphometric variables (26) and the correct interpretation could be important to understanding implant biology and adaptation of bone to mechanical loads imposed by the presence of the implant. The measurement of BFR can be attained using bone surface (BS) or BV as a referent. Typically, BS is the referent for measurements of BFR from trabecular bone compartment and BV serves as a referent for intracortical bone remodeling. While the typical units for BFR/BS are $\mu m^3/\mu m^2$/day, a meaningful way to report BFR data is in %/year. The rate of bone turnover varies in different bone types. For example, rate of cortical and trabecular bone turnover in humans are estimated to be at 2–10%/year and 25–30%/year, respectively (27). A research study may compare two groups and the rate of turnover may be reported in standard units. However, to derive meaningful numbers and interpret these values, it is useful to have nomenclature that is widely accepted.

Measuring bone adaptation and histomorphometry from microcomputed tomography (μCT) images

More recently, μCT has been used to study bone healing and adaptation. These μCT images provide 3D reconstructions of the region of interest. However, μCT still has not replaced dynamic histomorphometry but seems to have promise when measuring static histological measurement. These subtleties may have been overlooked and confound study designs in animal experiments (28). A major limitation of destructive examination by histology is that only a select number of 2D sections can be examined and do not reveal the true 3D nature of the implant interface. With the emerging use of microCT, there is even greater need to understand what data are useful and how this instrumentation compares with traditional histology. With implants, beam hardening and scatter have to be overcome (28) both *in vivo* and *ex vivo*. While some articles indicate that the same information can be obtained from μCT as with traditional histology, this is only true currently for primarily static measurements (28).

Critical failure of MSI – are they related to the design of the MSI or a problem inherent to the bone?

A major difference between MSI and endosseous implants is the need to remove the MSI after clinical use without trephining the mini-screw

implant. The ability to torque the MSI out without fracturing the implant or loss of bone in the alveolar process is critical. With this in mind, most MSI are smooth surface machined implants. More recently, displacement of MSI, with migration of the device toward the point of force application has been observed (29). In addition, the MSI can be displaced (creep) within the bone without being extruded or 'pulled out' (30). One key question is whether this migration of the MSI can be prevented. The nature and mechanism of MSI displacement within alveolar bone is unknown.

There is evidence to suggest that the alveolar process provides a unique milieu for implantation. It is well known that the volume of bone is small in the inter-radicular locations and placement of a screw close to the periodontal ligament results in increased probability that it will loosen and fail (31). It is likely that bone within the alveolar process experiences greater strains than basal bone in the jaw and such strains may result in overloading of the implant interface or even predispose the MSI to failure in this hostile environment (32).

Initial reports of displacement of MSI when subjected to orthodontic load were presented from 2D cephalometric data as early as 2004 (29). Subsequent reports with 3D cone beam studies suggest that MSI could be displaced by ~1 mm with a maximum value in one device of 4 mm (33). Others indicated that MSI used in the maxilla had an average displacement of 0.78 mm, however, some of the MSI had a displacement close to 2 mm (12). A clinical study reports the surface modification results in no difference in the survival rates of MSI used for orthodontic anchorage in the mandible and maxilla over a ~5-month period (34). However, a larger C implant (sand blasted, large grit and acid etched coated and 1.8 mm diameter) in a 9-month study in the maxilla for en-masse canine retraction indicates from the CBCT data that the MSI remain stationary (35). It is not a common practice to currently use the surface modified MSI. However, it seems that an implant with surface modification and of an appropriate diameter may provide more rigidity.

Can varying the diameter of the MSI in intra-alveolar and extra-alveolar bone anchorage sites to enhance rigidity?

Initially when skeletally anchorage was introduced to orthodontics, the anchors were used in an extra-alveolar location (e.g., retromolar implants, zygomatic wires). It was only with the introduction of smaller (1.5 vs. 3.75 mm diameter) mini-implants that inter-radicular placement was attempted (36). In addition, a major advantage of MSI is the ease by which they can be placed by the orthodontist accurately at the desired site from which load could be applied (1). This overcomes the need for patient referral, the additional cost and time for device placement by a surgeon.

One of the questions that have not been systematically addressed is the ideal diameter of MSI. The diameter has been determined primarily by the site of placement. For example, when MSI are placed between roots of maxillary molars for intrusion of maxillary posterior segment, a device with a diameter of 1.3 mm will allow for adequate bone for placement/retention and prevent impingement on adjacent roots (37). As BV and vital structures are not a consideration in extra-alveolar sites, it should be possible to use wider diameter implants, should they provide greater rigidity and service. Systematic studies will be needed to address these questions.

The focus of this article is limited and other methods to test for a successful implant such as insertion torque, removal torque, pull out testing, fatigue loading and other standard tests have not been discussed but are acknowledged.

Conclusions

Mini-screw implants continue to be plagued with a relatively high failure rate, and this failure challenges their clinical acceptance in the long term. The importance of osseointegration in the physiology and retention of MSI continues to evolve

and methods for scientific examination of newer designs are outlined. Lack of rigidity of MSI with resulting displacements within the bone needs to be investigated. Novel skeletal anchor designs will be required to overcome the limitations imposed by the unique alveolar bone physiology.

Clinical relevance

Mini-screw implants are commonly used to enhance orthodontic anchorage. However, the failure rates of MSI remain high. This review explores and describes the bone adaptation physiology to MSI and suggests outcome measures that are important to include in experimental animal studies. Finally, this review attempts to provide research areas that could be investigated and would allow for novel and successful designs of MSI.

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