Oral Diseases (2007) 13, 261–269. doi:10.1111/j.1601-0825.2007.01365.x

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INVITED REVIEW

Craniofacial osseointegration

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In year 2007, 30 years have elapsed since the first patient was supplied with a craniofacial osseointegrated implant. The reason for implanting in this patient was a severe conductive hearing loss, which necessitated the use of a bone conduction hearing aid. By utilizing the possibility to transmit sound to the cochlea via direct bone conduction, a new era in audiology was established. Further applications of osseointegration in the craniofacial field is related to the rehabilitation of patients with defects from cancer therapy, malformations, traumatic amputations and burns. Specific fields of osseointegration in this respect are due to possible side effects from radiotherapy and chemotherapy that will affect osseointegration negatively. Other aspects are related to osseointegration in children. This review will focus on the knowledge gained during the first 30 years of craniofacial osseointegration.
Oral Diseases (2007) **13**, 261–269

Keywords: osseointegration; craniofacial; bone-anchored hearing aid; prosthetics; cancer; malformations

Introduction

Professor Per-Ingvar Brånemark in 1977 coined the term 'osseointegration'. Although the definition has varied slightly during the years, principally it means 'a direct structural and functional connection between ordered', 'living bone and the surface of a load-carrying implant' (Brånemark, 1985). Osseointegration was originally used to anchor dental prostheses or bridges in the jaws to replace lost teeth (Brånemark *et al*, 1969). Since 1965, the concept of osseointegration has profoundly and definitely changed the fundaments of odontology (Brånemark *et al*, 1977; Adell *et al*, 1981; Albrektsson and Wennerberg, 2005). It is expected that in the year 2007, more than 8 million osseointegrated implants will be installed in more than 3 million patients for rehabilitation of total or partial edentulousness. Likewise, it has changed the fundaments of those specialities working outside the oral cavity. These include otolaryngology, head and neck surgery, maxillofacial surgery, plastic surgery, orthopedic-, and hand surgery. The number of patients rehabilitated with these parts of the concept is fewer, but it is estimated that more than 90 000 implants have been installed in more than 45 000 patients until year 2007. This review will focus on the rehabilitation of craniofacial defects – outside the oral cavity – utilizing the osseointegration concept.

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Received 13 December 2006; accepted 14 December 2006

Historical aspects

After thorough laboratory work in the 1950s, Brånemark installed the first osseointegrated implant in a human in 1965. It was used for the rehabilitation of an edentulous patient. During a 12-year period, further edentulous patients were included in clinical studies, and in 1977, after examination, the concept of osseointegration was accepted by the Swedish Medical Authorities. The very same year, the first patient had the first extraoral osseointegrated implant installed at our department. This patient was an elderly male with problems of hearing. He was earlier utilizing a bone conduction hearing aid. This aid functions by pressing the vibrator via a steel band to the skull, and it is known to cause pain due to pressure on the skin when using the aid for longer periods. In 1979, a patient with an ear defect caused by cancer was operated upon and supplied ear prosthesis in our department. This was followed by osseointegration in other regions of the craniofacial skeleton as the orbit, nose, and midface during the following years. By 1986, we had altogether operated 100 patients for different craniofacial defects, and then organized the first international workshop on craniofacial osseointegration. The concept for anchoring craniofacial prostheses on osseointegrated implants was accepted by the Food and Drug Administration (FDA) in 1985 and FDA accepted the concept to anchor hearing aids on implants in adults in 1995 and in children 1998.

In 1985, osseointegrated implants were used also in hand surgery to replace defect finger joints (Hagert *et al*, 1985), and in the beginning of the 1990s the concept was used for orthopedic reasons for rehabilitation of

amputees' fingers, hands, arms and legs (Brånemark *et al*, 2001).

Developmental steps

To be able to develop a craniofacial osseointegration concept that worked in the clinic, certain steps had to be undertaken. Different kinds of implants were developed from those used in the oral cavity. These were made from commercially pure (C.p.) titanium and were generally shorter or 3–5 mm long, threaded and with the same machined surface as the oral implants. It was further found important to attach a flange in the coronal part of the fixture. The reason for this was the belief that after a longitudinally directed trauma to the implant the flange would prevent it to be pushed into the brain. This has also been shown to be a safe security measure, as several trauma cases have occurred, but only a minority has caused fractures of the skull bone, and none has caused a severe damage (Tjellström, 1989).

The thickness of the skull bone determines the length of the fixtures. Adult temporal bone is usually 4 mm thick in the temporal line, which is also the length of the most commonly used fixtures. In the frontal bone, zygoma and maxilla, longer fixtures are possible to install. With the aim to obtain bicortical anchorage, sometimes 5, 8, 10 mm or even longer implants have been inserted (Tjellström, 1989; Granström, 2005).

The first abutment that was originally used was also of an intraoral type, but with time, extraoral abutments of different types were developed. These include abutments for the bone-anchored hearing aid (BAHA) and abutments for bone-anchored epistheses (BAE). Due to growth of the skin over the abutment, it was soon found necessary to change surgery and to reduce the thickness of the subcutaneous tissue. It was also found that those patients who had split skin grafts in conjunction with the skin penetration experienced the least skin penetration problems (Tjellström, 1990).

When installing osseointegrated implants in children, the skull bone is much thinner, sometimes only 1–3 mm. This has necessitated the development of augmentation techniques to be able to anchor fixtures in appropriate areas. This can be carried out in several ways, but a simple technique is to use semipermeable membranes during first stage surgery (Granström and Tjellström, 1999). By utilizing this technique, 1–2 mm bone can be gained during a 6-month healing period, thus making it possible to install a 4-mm long fixture also in children. The semipermeable membrane is then removed at the second stage surgery.

Osseointegration in irradiated bone was early believed to be contraindicated. Cancer patients can, however, benefit a lot by osseointegrated implants, and hence the technique was used also in these. With time, it was, however, found that implant failures were higher in this population and certain other drawbacks as soft tissue dehiscences and osteoradionecrosis also appeared (Granström, 2003). Using knowledge that irradiated bone shows a slower healing rate, it is still possible to use the concept in these patients by increasing the healing time. Other precautions as using adjunctive hyperbaric oxygen therapy (HBO) to prevent side effects from radiotherapy have also shown to be effective (Granström, 1998).

The skin penetration is the factor that has caused the most abundant clinical problems related to craniofacial osseointegration. By using a clinical grading system based on the condition of the skin, it has been possible to determine the amount of adverse skin reactions that occur (Holgers *et al*, 1987). Medical and surgical attempts to reduce these skin reactions have then been undertaken.

Factors of importance to obtain osseointegration

There are six factors of importance to obtain osseointegration (Albrektsson and Jacobsson, 1987). The first is the material of the fixture to be implanted. C.p. titanium is the most commonly used. C.p. titanium is known to integrate in the bone without causing adverse effects. It can remain incorporated into the bone for many decades, and be used as anchorage for different prostheses. Other metals as vanadium, tantalum certain ceramics, aluminum hydroxide and hydroxylapatite are also known to integrate into the bone to a certain degree.

The macrostructure of the implant has importance for the integration. A screw-shaped implant often shows good primary stability, whereas a cone-shaped implant might be lost because of initial micro movements and hence poor stability.

The microstructure of the implant is also known to affect osseointegration. The original Brånemark implant was machined and hence had a relatively smooth surface. It is today known that a very smooth surface will result in poor integration, but with minor resorption. A very rough surface will result in rapid integration, but secondary inflammation and resorption that can jeopardize integration later on (Albrektsson and Wennerberg, 2004).

The bone bed into which the implant is installed is of importance. Thus, there is a difference related to if the implant is installed in a child with relatively soft and immature bone, compared with an adult. The very old person, with osteoporosis will integrate the implant to a lesser degree, and implants have been lost to a higher proportion among these (Drinias *et al*, 2007). Patients who have been irradiated or who sustained burns will have an altered texture of bone that will reduce the capacity to integrate implants (Granström *et al*, 1993a).

The surgical technique is of major importance. It is necessary that surgery should be non-traumatic, without causing the drilling temperature to rise by more than a few degrees. The fixture should only be handled by titanium instruments and never touched by the gloved hand. It is further important that the surgical field should be protected from fibers, powder and other substances that might hinder osseointegration (Tjellström *et al*, 1983).

The load of the implant should preferably be in the longitudinal direction. Thus it is important to avoid rotational or cantilever forces, once the implant has

integrated. If forces are distributed in the longitudinal direction, even very high loads can be withstanded by the implant during many years of function (Tjellström, 1989).

Factors of importance to lose osseointegration

Loss of integration can be obtained by overload, torsion forces or direct trauma to the implant. Overload might be the result of long extensions of the bar construction or by misplaced implants. Minor torsion forces might induce microfractures in the bone that with time can rupture the delicate integration. Lack of adequate counterforces during tightening of the abutment, might result in immediate implant loss. Tightening of individual magnets used as retention without counterhold might as well cause implant failures (Tjellström, 1989).

The quantity of bone, and also the quality of bone might determine the forces necessary to lose an implant. The most well-known cause for implant failure, is the bone that has been irradiated as part of cancer treatment. Chemotherapy also affects implant survival to a similar degree as radiotherapy. Other factors that might affect implant survival are osteoporosis, steroid medication and diabetes mellitus (Granström, 2005).

Preoperative planning, patient selection and contraindications

To obtain optimum rehabilitation results, it is important to use a team approach (Van Oort *et al*, 1994; Schwipper and Tilkorn, 2000; Wolfaardt *et al*, 2005). Each team can have an individual setting, but it generally comprises a surgeon (ENT, oral, maxillofacial or plastic surgeon), a prosthodontist or anaplastologist and a nurse as coordinator. It is valuable to have a radiologist and often other specialists as speech pathologist, audiologist, etc., whenever needed.

Planning craniofacial osseointegration is a multifactorial process and requires tailoring for each patient. An adequate evaluation of the patient's general health status including psychological profiling prior to surgery is important. A computed tomography (CT) scan or other radiographic evaluation of the bone quantity and quality is essential. Hemoglobin count and other necessary laboratory data are gathered. If the patient has been able to meet another patient with a similar defect, this is helpful for the understanding of the planned rehabilitation. At the performance of surgery, it is essential that the prosthodontist/anaplastologist gives instructions as to the ideal position, number and angulations of implants. CT scan recordings can be analyzed and manipulated in an information technology implant planning application (Wolfaardt *et al*, 2003). Implant planning software allows bone volumes and densities to be assessed. Implant installation can be simulated, depth of soft tissues overlying the area can be assessed and emergence profiles be considered. A more sophisticated approach to craniofacial implant planning has been described (Watson *et al*, 1993). This technique makes use of overlaying laser scanning of soft tissues that is digitally overlaid on CT scanning and then CNC milling is used to locate the desired implant positions. Rapid prototyping with sterolithography has been used in patients with defects of the craniofacial region. The rendered acrylic model of the region assists in the positioning of implants (Wolfaardt *et al*, 2005).

The indications for implant-based surgery may vary considerably. It is important to judge the alternatives to the planned rehabilitation. The motivation of the patient may likewise vary considerably. It is also important to find out if the patient has realistic expectations on what is possible to obtain. The age of the patient in relation to maturity, and the influence of parents or other relatives must be judged before starting the rehabilitation. Previous surgery in the field of operation and combined radiotherapy/chemotherapy may jeopardize implant installation.

Contraindications to craniofacial osseointegration may be psychiatric disease, alcohol and drug abuse, senility or other disease making the patient unable to take care of implant care. Patients not planning to participate in follow-up programs may also be contraindicated. It is imperative that the patient be prepared to take care of the implant in the followup time.

Any condition that influences the bone to remodel may influence the process of osseointegration. The literature cites numerous potential local and systemic factors that may negatively affect craniofacial osseointegration. It appears that smoking reduces implant survival, although well-designed studies are lacking. The literature on smoking and implant survival addresses dental implants and not craniofacial osseointegrated implants (Esposito *et al*, 1998).

Equipment and tools

The original craniofacial implant was introduced by Nobelpharma, later Nobel Biocare, Gothenburg, Sweden. This implant system, the Brånemark osseointegration system® was developed from the oral concept utilizing the same drilling equipment, implant surface and drill machine. This implant system has remained relatively unchanged during the years. Only minor alterations of the implants have been undertaken as changed angulations of the abutment for the BAHA. Different angulated abutments – console abutments – have also been developed for use in the orbit. A new self tapping fixture is presently introduced in the market.

There are today several other systems that use other surfaces of the fixture (Conexcao®, Otorix®, Straumann®, ITI®), but they all are principally based on the original implant, and hence the same drilling equipment can be used also for these. Surfaces other than the original machined are as well available today.

Surgery for craniofacial osseointegration

Surgery is generally performed under local anesthesia with appropriate premedication. General anesthesia is recommended in children and in persons in whom the drilling procedure will be extended. The surgical installation of screw-shaped osseointegrated implants is well described in the literature (Tjellström, 1985, 1989). The original surgical technique used a two-stage approach with 3–4 months' healing between the stages of surgery.

Later, a one-stage approach in the mastoid was described (Tjellström and Granström, 1995). The two-stage approach continues to be advocated for pediatric patients, the orbit, midface applications and in patients who have been irradiated (Granström *et al*, 1993a, 2001; Granström, 2005). Principally, two drilling techniques are used when installing extraoral fixture. During the first technique high speed (2000 r.p.m.) drills are used to make a hole in the bone at the decided place for the fixture. By using sharp drills and profound irrigation, the temperature is kept low, and the bone cells will remain alive. After the site of the implant has been prepared, low speed drilling (15 r.p.m.) is taking place, and the width for the fixture is finally decided and the fixture installed. Today, most often a self-tapping implant is used whenever possible. Threading might be necessary in a very hard and brittle bone.

In the adult non-irradiated patient, the attachment of the abutment can proceed immediately after implant installation. In children and irradiated patients, surgery is still conducted in two stages with a healing time of 3–6 months in between. Reduction in the subcutaneous tissue then takes place. This is one of the most important steps, as a thick skin will result in more adverse skin reactions (Reyes *et al*, 2000). The subcutaneous tissue is removed at a long distance away from the implant to allow a smooth and thin lining of the skin immediately close to the abutment. After surgery, a healing cap with an ointment-soaked gauze rapped around the abutment is used to prevent postoperative bleeding and infection, and to keep the skin pressed to the bone surface during the initial healing period.

Postoperative treatment

Most surgeries at our department have been performed under local anesthesia and as day-care surgery. Thus, the patient usually goes home the same day of surgery. The surgical dressing can be removed on the day after surgery while the healing cap and soaked gauze kept for a week. The patient then comes back to the outpatient clinic after a week when the stitches are removed. After the skin and soft tissue has healed, the fitting procedure for the BAE or BAHA can begin.

Self-care

It is important that the patient is correctly instructed on how to take care of the skin-penetration site. Debris will invariably collect around the neck of the abutment. This debris is a mixture of keratinocytes and evaporations and should be removed every day with a soft toothbrush or cotton tip, soap and water. If the patient can handle the skin penetration adequately, a long-term reaction free skin is possible to obtain. The patient should be included in a self-care program with daily cleanings, using soap and water, dental floss and soft toothbrush in specific areas. The patient should also attend the clinic for regular follow-up visits, three to four times the first year and twice a year during the following years. At the visits the clinical scores are registered, cleaning is checked and reinstruction given when necessary.

Applications

General indications

The bone-anchored hearing aid

The bone-anchored hearing aid was developed to replace standard bone conduction hearing aids. Bone conduction aids work by pressing the vibrator to the skull via the skin. Better sound transmission is obtained when the steel band presses the vibrator hard on the skin. This is, however, often painful to the patient after a certain time of use. The BAHA functions by a direct sound transmission through the bone, via a permanent skin penetration. Thus the painful pressing of the skin is avoided, and also a better sound transmission is obtained (Tjellström and Håkansson, 1995). Several different types of the BAHA have been developed during the years (Snik *et al*, 2005). The BAHA Compact is the smallest device, suitable with those patients, often children with the best cochlear function. BAHA Classic is the standard ear level device, and will be gradually replaced by BAHA Divino, which is the first digital BAHA developed. The body-worn device BAHA Cordelle has the strongest output and is used by patients with the poorest cochlear reserve.

Audiological prerequisites for the BAHA is a maximal recommended bone conduction threshold of 45 dB hearing level (HL) taken as an average of 0.5, 1, 2, and 3 kHz for the ear level device. For the body-worn device, a maximal recommended bone conduction threshold of 60 db (HL) take as an average of 0.5, 1, 2, and 3 kHz.

Indication for BAHA is any patient needing a bone conductor. The most common reason for supplying a patient with BAHA is chronic ear disease, when a standard air conduction aid occludes the ear canal, and the ear starts to drain (Snik *et al*, 2005). The second most common reason is bilateral ear canal atresia. Conductive hearing loss in only hearing ear is also an indication, as is external otitis, which prevents the patient from using standard air conduction aids.

The prescription of bilateral BAHA is recommended in certain cases. This can be persons with specifically demanding occupations as teachers and musicians, with high demands on sound localization. The amplification from double BAHAs is in the range 5 dB (Priwin *et al*, 2004). Patients with unilateral ear canal atresia, can sometimes gain from a BAHA on the malformed side. This goes especially for children (Priwin *et al*, 2007). The latest indication for BAHA is single-sided deafness, in which patients can obtain some directional hearing from the shadow side (Snik *et al*, 2005).

Bone-anchored epistheses

Ear prosthetics. Cancer surgery, malformations, traumatic amputations or burns can cause ear defects. Alternatives to rehabilitate the patient may be to disclose the defect with a natural hair styling. This is fully satisfactory to some patients. Autogenous reconstruction has become a realistic procedure in the last decade (Firmin, 1998). Several plastic surgeons can make very natural looking autogenously reconstructed ears, and

this should therefore be the principal option. If the reconstruction fails, it can easily be removed, and an implant-retained episthesis be an alternative (Wilkes and Wolfaardt, 1994). Radiation therapy, scarring due to trauma or burns may compromise the local tissue so that autogenous reconstruction may be contraindicated and craniofacial osseointegration is the only realistic treatment option. Anatomically, the lower half of the ear is the most challenging to reconstruct (Wolfaardt *et al*, 2003). In those cases where a prosthesis is indicated, the anchorage could be by glue, undercuts, spectacles or by implants. Bone-anchored ear episthesis has an advantage over the earlier mentioned retention systems in that it is a safe, easy and secure anchoring method (Granström *et al*, 1993b). Where attempts of autogenous reconstruction have failed, craniofacial osseointegration provides a valuable salvage option. A particularly controversial aspect of treatment selection in ear reconstruction is in the pediatric patient with microtia. It is possible to place osseointegrated implants in children, but the question remains as to what is appropriate. If an autogenous reconstruction fails, the craniofacial osseointegration portion remains. However, if the patient rejects an implant-based prosthesis, an autogenous option might not be available to the patient. With the installation of implants, the microtic area is scarred and this may limit the potential for satisfactory autogenous reconstruction if indicated later. Consequently, it is important to ensure that the patient and parents are well informed of their options before treatment proceeds.

Orbit prosthetics. Defects of the orbit can appear because of cancer surgery, after certain eye diseases, traumatic ablatio and burns. Alternatives to disclose the defect can be to cover the defect with a patch or supply the patient with prosthesis anchored on spectacles, undercuts or glue. Autogenous reconstruction may be limited when the contents of the orbit have been exenterated or severely anatomically disrupted. Skin flaps may be used to provide coverage of the orbit but provide poor aesthetic results. A prosthesis based on osseointegrated implants is the best option for several reasons (Wilkes and Wolfaardt, 2000). Surgery is simple and straightforward, and the implant is easily removed if the patient changes his/her mind. An important aspect is that it is easy to inspect the tumor cavity if the patient wears a prosthesis. If a skin flap covers the defect, recurrent tumor will be detected later.

Nose prosthetics. Nose defects most often occur after cancer surgery, traumatic amputations (animal bites) and burns. Alternatives to rehabilitate the patient can be to cover the defect with a patch, or prosthesis anchored on spectacles, undercuts, glue or osseointegrated implants. Autogenous reconstruction of the nose is possible to make with high esthetical results, and might therefore be the first option for the patient (Weiss *et al*, 1998). In common with aspects of ear reconstruction, if the patient's medical status precludes surgery, residual tumor is present, there are no suitable donor sites, the patient will not tolerate the donor sites or by the patient's choice, autogenous reconstruction may be precluded. In these situations, craniofacial osseointegration becomes the treatment of choice. Where there has been severe loss of facial contour this may be best reconstructed with an implant retained nasal prosthesis. If one, however, decides to supply the patient with an implant-based episthesis for reasons of cancer observation, secondary autogenous reconstruction is still possible years later. That is another advantage with osseointegration, in that it is a reversible procedure if the patient changes his/her mind.

Midface prosthetics. Midface defects are often a result of cancer surgery, gunshot wounds, burns, and in some occasions caused by malformations, e.g. non-reconstructed lip, jaw and palate clefts. In limited defects of the midface, autogenous reconstruction, combining different grafting techniques might be the first choice. Where the defect extends to the oral cavity or orbit, where an autogenous reconstruction is not possible, osseointegrated implants may offer the most appropriate treatment option (Eckert and Desjardin, 1998; Harris *et al*, 1996; Schwipper and Tilkorn, 2000). In a number of cases, combined grafting and osseointegrated implants for prosthetics is favorable.

Major facial prosthetics. Major facial defects are often a result of cancer surgery, gunshot wounds or burns. The first option is often autogenous reconstruction, combining different grafting techniques. In those instances where orbit or nose is deficient, a prosthetic solution can be combined with autogenous reconstruction. Here, episthesis anchored on spectacles, undercuts, glue or implants is an option. In several cases, the combined grafting and osseointegrated implants for prosthetics is favorable.

Other areas in the craniofacial region
Where significant areas of hair loss have occurred, osseointegrated implants have been used to retain a hairpiece (Weischer and Mohr, 2000, Wolfaardt *et al*, 2005). While this is not a widely used application of craniofacial osseointegration, it may provide an option where wearing of a conventional wig, hairpiece, tissue expansion or hair transplantation is not possible.

Grafting as part of procedure
Especially in cancer patients, the defects from cancer surgery may be extensive, and there might be limited bone left, available for implant installation. The tissue may be further compromised if the patient has received irradiation and chemotherapy as part of cancer treatment. In these cases, grafting of the bone to the implant site may be an option. There are several techniques used to bring the bone, soft tissue and skin to the craniofacial region (Urken *et al*, 1989; Triplett *et al*, 2000). The specific technique utilized must often be adapted to the patient's specific defect. Placement of craniofacial implants at the time of surgical reconstruction has some advantages, particularly when the implants help to stabilize the graft in relation to the host bone. As fewer surgical procedures

are needed, patient morbidity is potentially reduced and the process may be cost-effective. Secondary implant insertion does, however, allow more precise planning of the optimum implant position and angulation (Triplett *et al*, 2000). Some authors do not support the use of primary installation of craniofacial implants in grafts, as the risk for misplacement is obvious. It is further reported a higher risk of loosening implants, risk for osteoradionecrosis and risk for survival of graft in those cases (Schmelzeisen *et al*, 1996; Schoen *et al*, 2001). The prognosis for implants placed in a vascularized bone graft is generally better than those placed in non-vascularized grafts, whether in a primary or secondary implant placement (Flood and Russell, 1998).

Results and follow-up

By the end of 2006, a total of 1453 patients had been rehabilitated by the osseointegration concept at our department. The most common reason for implantation was the BAHA (869 patients), followed by epistheses for ear reconstruction (342), orbit (116), different facial epistheses (42) and maxillary or mandibular defects (84). Of the reasons for rehabilitating a patient with an episthesis, cancer was the most common (422) followed by malformations (128), burns and trauma (37). More than 3000 osseointegrated implants have been installed in the craniofacial region without any serious complications until today. During 20 years of follow-up, implant failures have been approximately 10% (Tjellström and Granström, 1994; Reyes *et al*, 2000). There are certain factors that determine the implant failure rate. The temporal bone shows the lowest implant failure rate or 8% over a 10-year period. This is a relatively compact bone with properties similar to that of the mandible. In this bone, it is possible to detect an age-dependent difference in failure rate (Drinias *et al*, 2007). Thus the oldest patients showed the highest failure rates, probably as a result of increasing osteoporosis. In the other craniofacial regions, the highest implant failure rates were seen in the frontal bone (50%) and zygoma (20%) (Granström *et al*, 1994). This has been found related to these bones being irradiated more often than the other regions (Granström, 2005).

The skin penetration

The skin penetration site is the single factor that has caused craniofacial osseointegration the most significant clinical problems (Abu-Serriah *et al*, 2001). Despite extensive subcutaneous reduction during surgery, some patients will experience a red and moist skin, and sometimes granulation tissue forms around the abutment. Compared with oral osseointegration, some differences are obvious. The gingiva is constructed to have a mucosal penetration. Saliva and the cleaning ability of the oral tongue contribute to good condition (Steflick *et al*, 1991; MacKenzie and Tonetti, 1995). Nevertheless, most patients can obtain and maintain a reaction free skin penetration for many years (Tjellström *et al*, 1983, 1985). To be able to control the adverse reactions, a skin condition scoring system was developed (Holgers *et al*, 1987) where 0 is no reaction; 1: reddish; 2: red and moist; 3: granulation tissue; 4: skin infection to such a degree that the abutment has to be removed. The scores vary depending on how many implants have been inserted, the region in which the implants were inserted, the retention system used and the age of the patient. Thus 92.5% of BAHA users had a reaction free skin (score 0), 91.1% of orbital prosthesis users and 89.3% of auricular prosthesis users were similarly free of complications (Holgers *et al*, 1992). Young children tend to have low reaction scores during childhood when the parents take care of the implants. In adolescence, however, the adverse reactions tend to increase as the care of implants is neglected (Granström *et al*, 1993b). Of those patients experiencing adverse reactions, 15% contribute to more than 70% of all adverse reactions and the reason for the skin reactions can be explained by insufficient home care (Tjellström, 1989). Over longer times, the number of adverse skin reactions decline as an indication that the patients learn how to take care of the skin-penetration site (Reyes *et al*, 2000). Some authors have suggested that the subcutaneous tissue in the peri-abutment region should be thinned or a split thickness skin graft should be placed so as to limit the tissue movement (Albrektsson *et al*, 1987; Tjellström, 1990; Tolman and Desjardins, 1991; Westin *et al*, 1999). Limiting movement will, theoretically, decrease the shearing forces at the soft tissue–implant abutment interface, and better maintain a barrier against bacterial ingrowth. However, some may argue that trimming of the subcutaneous tissues or split skin grafting can result in scarring and so compromise the vascularity of the peri-implant soft tissue, and increase the potential for adverse skin reactions. Surgical manipulation of the subcutaneous tissue may also alter connective tissue–epithelial interactions and undermine the integrity of the implant–soft tissue interface. The importance of healthy underlying the connective tissues has been well recognized, but it is not clear just how thick the peri-abutment skin should be (Abu-Serriah *et al*, 2003).

Maintaining skin problems

When the patient attends the clinic with a grade 1 reaction, we have intensified the cleaning at the follow-up visit, re-instructed the patient and given him an earlier time for the next check-up visit. When grade 2 reactions occur we have done as for grade 1 and furthermore prescribed local ointment (Terracortril + Polymyxin B®; Pfizer, Dublin, UK), which contains antibiotics, antimycotics and steroids. This is applied 2–3 times a day for the next week and the patient returns to the clinic for our inspection. When grade 3 reactions occur we have done as for grade 2 but also wrapped a Terracortril and Polymyxin B-soaked tampon around the abutments with changes for a week. An alternative could be to remove the bar and put on the healing caps around which the tampon is wrapped. If the tissue reaction is not under control, surgical removal of the granulation tissue followed by new skin grafting is suggested. A grade 4 reaction means that all attempts to correct a grade 3 reaction have failed. We then remove the abutment and leave the skin for

secondary healing. If necessary a new abutment could be reconsidered later on.

Certain skin conditions need specific attention. Acne vulgaris can create problems in the skin penetration area during adolescence, and sometimes afterwards. It can generally be handled by local cleaning or by drugs prescribed for the disease. Seborrhoic eczema can cause local problems, especially in the temporal region. Local treatment with steroids can be helpful as grafting of non-eczematous skin. Psoriasis can be treated in a similar way, but may need proper planning to avoid primary installation in the lesion. Patients with diabetes mellitus often have a reduced healing rate, and skin necrosis is more common. Secondary healing is often uneventful in any case. Keloid formation can be abundant, especially in burns patients. Local excision combined with injection of steroids might help reduce the problem.

Irretractable skin problems can be due also to loose fixtures or abutments. These should be checked and retightened upon the patient follow-up visits. Misplaced implants, with too narrow positioning might also affect the skin condition, as it can be very difficult for the patient to clean (Tjellström, 1989; Reyes *et al*, 2000).

Osseointegration in irradiated patients

This topic has caused some controversy during the years (Donoff, 2006; Granström, 2006). The fundamental question is whether radiotherapy causes negative effects on osseointegration or not. Increased knowledge today shows that a number of factors affect implant survival in the irradiated bone. These include radiotherapy given before or after implant installation (Granström *et al*, 1993a,c; Granström, 2005). The combined pre- and postoperative irradiation is particularly damaging to implant integration (Granström and Tjellström, 1997). Factors that affect implant survival, such as irradiation dose and fractionation, chemotherapy, time from radiotherapy to implant surgery, and also other factors such as fixture length and prosthetic retention affect the results. Implant survival also depends on the length of time that one follows the patient. (Granström, 2005). Despite the fact that implant survival might be affected by radiotherapy, the benefits the patient can gain from receiving implants are so high that it is recommended. However, it is also stressed that cancer patients who are supposed to receive osseointegrated implants, should be treated at institutions well used to handling cancer patients. Risk for induction of osteoradionecrosis is always present, and it is of the utmost importance that such side effects are avoided. Adjunctive use of hyperbaric oxygen therapy can reduce that risk (Granström *et al*, 1994, 1999).

Osseointegration in children

In oral osseointegration it is well known that installation of osseointegrated implants before finished growth of the jaws results in unfavorable implant positioning (Ödman *et al*, 1991). However, in extraoral osseointegration children may also need to be implanted. These include especially syndromic children with bilateral ear malformations. Not knowing the lowest age possible to implant children, a gradual lowering of age was used to gain knowledge of factors of importance for obtaining stable implants in this patient category. The thickness of the parietal and temporal bones is a limiting factor for implant installation. Measuring the bone thickness during surgery shows that a lower age of approximately 4 years is necessary to have a reasonably thick bone for a 4-mm fixture to be installed (Priwin and Granström, 2005). In children who do not have this required thickness of the skull bone, it is still possible to install fixtures with bone augmentation by use of semipermeable membranes (Granström and Tjellström, 1999). An increased bone thickness of 1–2 mm is possible to obtain during a healing period between the first and the second stage surgery of 4–6 months (Granström and Tjellström, 1999). With the use of this technique it has been possible to implant children down to an age of 1 year without significantly higher implant failures.

Developmental projects

There are several unresolved problems related to craniofacial osseointegration, which are subject to research at our institution. The skin penetration is the most prominent clinical problem in many clinics utilizing craniofacial osseointegration. Despite surgical techniques leading to a thin, non-mobile skin penetration, several patients develop gradually thicker skin with related problems due to cleaning difficulties. This might lead to dermatitis and possible risk for implant failure with time. We are seeking an increased understanding of the biological behavior of the skin. Our hypothesis is that several of the factors of importance for inflammation of the periodontium is present in the skin as well. Thus, introducing methods of determining which inflammatory systems are active might help to understand why dermatitis occurs at the penetration site. We are looking further for alternative medical and surgical treatment options.

Irradiation of the bone bed is a topic of further study. Knowing that implant failures are higher in the previously irradiated bone, new approaches to improve osseointegration are necessary. This project is a multicentre study performing a randomized, controlled study comparing normobaric air to hyperbaric oxygen. Interested readers can enroll patients on the website http://www.oxynet.com. In future studies pharmacological effects, e.g. from growth factors in the compromised tissues are to be studied. New implant materials are tested in several controlled studies. These include implants of different sizes and shapes, with modified surfaces. These studies also utilize non-interventional measurement of osseointegration as resonance frequency analysis and different radiological techniques. Computer-aided techniques to better control fixture placement will be utilized. Osseointegration in children is subject of further studies with the aim to determine the optimum age for implantation. Several of the children have reduced bone at the implant site necessitating bone augmentation. The future growth of the temporal bone is a factor that needs to be controlled. With time, the fixtures will be buried in an inferior position, which might need further surgery to adjust. In a research project, a superficially positioned implant will be inserted

already from the beginning to compensate for future growth. Two projects studying implantable BAHAs, and BAHA for single-sided deafness are conducted. These projects aim at rehabilitating persons with hearing handicaps that are not possible to treat today.

Aspects for the future

The development of craniofacial osseointegration will continue during the next decades and further. New macrostructures that can affect bone interactions will be developed. These could include different angulations of the threads, addition of microgrooves and changed anatomy of the implant neck and additional undercuts in the fixture as described for oral implants (Miranda-Burgos, 2006).

New surfaces that will stimulate bone formation and add years to successful osseointegration will be developed. New surgical techniques that are faster and simpler both for the patient and surgeon will be developed. Growth factors, stem cells and other pharmacological drugs will help us to improve osseointegration in compromised tissues (Thor, 2006). We will have help from non-intervention evaluation of the implants to understand better the biology of osseointegration. New prosthetic materials that help us rehabilitate patients with severe craniofacial defects will be developed.

It will be possible to build together form and function combining osseointegration with microelectronics, e.g. as described by Klein *et al*, 1999). And more is to come that we cannot tell today.

References

Abu-Serriah MM, McGowan DA, Moos KF, Bagg J (2001). Outcome of extraoral craniofacial endosseous implants. *Br J Oral Maxillofac Surg* **39:** 269–275.

Abu-Serriah MM, McGowan DA, Moos KF, Bagg J (2003). Extra-oral endosseous craniofacial implants: current status and future developments. *Int J Oral Maxillofac Surg* **32:** 452–458.

Adell R, Lekholm U, Rockler B, Brånemark P-I (1981). A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int J Oral Surg* **10:** 387–416.

Albrektsson T, Jacobsson M (1987). Bone-metal interface in osseointegration. *J Prosthet Dent* **60:** 75–84.

Albrektsson T, Wennerberg A (2004). Oral implant surfaces: Part 1 – review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. *Int J Prosthodont* **17:** 544–564.

Albrektsson T, Wennerberg A (2005). The impact of oral implants – past and future, 1966–2042. *J Can Dent Assoc* **71:** 327.

Albrektsson T, Brånemark PI, Jacobsson M, Tjellström A (1987). Present clinical application of osseointegrated percutaneous implants. *Plast Reconstr Surg* **79:** 721–731.

Brånemark P-I (1985). Introduction to osseointegration. In: Brånemark P-I, Zarb GA, Albrektsson T, eds. *Tissue-integrated prostheses. Osseointegration in clinical dentistry*. Quintessence Publishing Co.: Chicago, IL, pp. 11–76.

Brånemark PI, Breine U, Adell R, Hansson BO, Lindström J, Ohlsson Å (1969). Intra-osseous anchorage of dental prostheses. I. Experimental studies. *Scand J Plast Reconstr Surg* **3:** 81–100.

Brånemark PI, Hansson B, Adell R *et al* (1977). Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10 years period. *Scand J Plast Reconstr Surg* **11**(Suppl. 16)**:** 1–132.

Brånemark R, Brånemark P-I, Rydevik B, Myers RR (2001). Osseointegration in skeletal reconstruction and rehabilitation: a review. *J Rehabil Res Dev* **38:** 175–181.

Donoff RB (2006). Treatment of the irradiated patient with dental implants: the case against hyperbaric oxygen treatment. *J Oral Maxillofac Surg* **64:** 819–822.

Drinias V, Granström G, Tjellström A (2007). High age at the time of implant installation is correlated to increased loss of osseointegrated implants in the temporal bone. *Clin Oral Implants Rel Res*, in press.

Eckert SE, Desjardin RP (1998). Prosthetic considerations. In: Brånemark P-I, Tolman DE, eds. *Osseointegration in craniofacial reconstruction*. Quintessence Publishing Co.: Chicago, IL, pp. 87–94.

Esposito M, Hirsch J-M, Lekholm U, Thomsen P (1998). Biological factors contributing to failure of osseointegrated oral implants. (2). Etiopathogenesis. *Eur J Oral Sci* **106:** 721–764.

Firmin F (1998). Ear reconstruction in cases of typical microtia. Personal experience based on 352 microtic ear corrections. *Scand J Plast Reconstr Hand Surg* **32:** 35–47.

Flood TR, Russell K (1998). Reconstruction of nasal defects with implant-retained nasal prostheses. *Br J Oral Maxillofac Surg* **36:** 341–345.

Granström G (1998). Hyperbaric oxygen therapy as a stimulator of osseointegration. In: Yanagita N, Nakashima T, eds. *Advances in otorhinolaryngology*, Vol. 54. Karger Publishing Co.: Basel, pp. 33–49.

Granström G (2003). Radiotherapy, osseointegration and hyperbaric oxygen therapy. *Periodontol 2000* **33:** 145–162.

Granström G (2005). Osseointegration in irradiated cancer patients. An analysis with respect to implant failures. *J Oral Maxillofac Surg* **63:** 579–585.

Granström G (2006). Placement of dental implants in irradiated bone: the case for using hyperbaric oxygen. *J Oral Maxillofac Surg* **64:** 812–818.

Granström G, Tjellström A (1997). Effects of irradiation on osseointegration before and after implant placement: a report of 3 cases. *Int J Oral Maxillofac Implants* **12:** 103–107.

Granström G, Tjellström A (1999). Guided tissue-generation in the temporal bone. *Ann Otol Rhinol Laryngol* **108:** 349–354.

Granström G, Tjellström A, Brånemark P-I, Fornander J (1993a). Bone-anchored reconstruction of the irradiated head and neck cancer patient. *Otolaryngol Head Neck Surg* **108:** 334–343.

Granström G, Bergström K, Tjellström A (1993b). The bone-anchored hearing aid and bone-anchored episthesis for congenital ear malformations. *Otolaryngol Head Neck Surg* **109:** 46–53.

Granström G, Tjellström A, Albrektsson T (1993c). Post-implantation irradiation on titanium implants for head and neck cancer treatment. *Int J Oral Maxillofac Implants* **8:** 495–501.

Granström G, Bergström K, Tjellström A, Brånemark P-I (1994). A detailed study of titanium fixture implants lost in irradiated tissues. *Int J Oral Maxillofac Implants* **9:** 653–662.

Granström G, Tjellström A, Brånemark P-I (1999). Osseointegrated implants in irradiated bone. A case-controlled study using adjunctive hyperbaric oxygen therapy. *J Oral Maxillofac Surg* **57:** 493–499.

Granström G, Bergström K, Odersjö M, Tjellström A (2001). Osseointegrated implants in children. Experience from our first 100 patients. *Otolaryngol Head Neck Surg* **125:** 85–92.

Hagert C-G, Brånemark P-I, Albrektsson T, Strid K-G, Irstam L (1985). Metacarpophalangeal joint replacement with osseo-integrated endoprostheses. *Scand J Plast Reconstr Surg* **20:** 207–218.

Harris L, Wilkes GH, Wolfaardt JF (1996). Autogenous soft-tissue procedures and osseointegrated alloplastic reconstruction: their role in the treatment of complex craniofacial defects. *J Plast Reconstr Surg* **98:** 387–392.

Holgers KM, Tjellström A, Bjursten LM, Erlandsson BE (1987). Soft tissue reactions around percutaneous implants. A clinical study on skin-penetrating titanium implants used for bone-anchored auricular prostheses. *Int J Oral Maxillofac Implants* **2:** 35–39.

Holgers KM, Roupe G, Tjellström A, Bjursten LM (1992). Clinical, immunological and bacteriological evaluation of adverse reactions to skin-penetrating titanium implants in the head and neck region. *Contact Dermatitis* **27:** 1–7.

Klein M, Menneking H, Schmitz H, Locke HG, Bier J (1999). A new generation of facial prosthesis with myoelectrically driven upper lid. *Lancet* **353:** 1493.

MacKenzie IC, Tonetti MS (1995). Formation of normal gingival epithelial phenotypes around osseo-integrated oral implants in humans. *J Periodontol* **66:** 933–943.

Miranda-Burgos P (2006). On the influence of micro- and macroscopic surface modifications on bone integration of titanium implants. Thesis, Göteborg University, Sweden, pp. 1–60.

Ödman J, Gröndahl K, Lekholm U, Thilander B (1991). The effect of osseointegrated implants on the dento-alveolar development. A clinical and radiographic study in growing pigs. *Eur J Orthod* **13:** 279–286.

Priwin C, Granström G (2005). The bone-anchored hearing aid in children: a surgical and questionnaire follow-up study. *Otolaryngol Head Neck Surg* **132:** 559–565.

Priwin C, Stenfelt S, Granström G, Tjellström A, Håkansson B (2004). Bilateral bone-anchored hearing aids (BAHAs): an audiometric evaluation. *Laryngoscope* **114:** 77–84.

Priwin C, Jönsson R, Hultcrantz M, Granström G (2007). BAHA in children and adolescents with unilateral or bilateral conductive hearing loss, a study of outcome. *Int J Pediatr Otorhinolaryngol* **71:** 135–145.

Reyes R, Tjellström A, Granström G (2000). Evaluation of implant losses and skin reactions around extra-oral bone anchored implants: a 0 to 8 year follow-up. *Otolaryngol Head Neck Surg* **122:** 272–276.

Schmelzeisen R, Neukam FW, Shirota T, Specht B, Wichman H (1996). Postoperative function after implant insertion in vascularized bone grafts in maxilla and mandible. *Plast Reconstr Surg* **97:** 719–725.

Schoen PJ, Raghoebar GM, Van Oort RP *et al* (2001). Treatment outcome of bone-anchored craniofacial prostheses after tumour surgery. *Cancer* **92:** 3045–3050.

Schwipper V, Tilkorn H (2000). Combined extra- and intraoral defects: their repair by reconstructive surgery and dental and facial prostheses. *J Facial Somato Prosthet* **6:** 29–38.

Snik AFM, Mylanus EAM, Proops DW *et al* (2005). Consensus statements on the BAHA system: where do we stand at present?. *Ann Otol Rhinol Laryngol* (Suppl. **195):** 1–12.

Steflick DE, McKinney RV, Parr GR, Sisk AL, Koth DL (1991). What do we know about the interface between the implants and the soft tissues? *J Oral Maxillofac Surg Clin North Am* **3:** 775–793.

Thor A (2006). On platelet-rich plasma in reconstructive dental implant surgery. Thesis. Göteborg University, Sweden, pp. 1–127.

Tjellström A (1985). Percutaneous implants in clinical practice. *Crit Rev Biocompat* **1:** 205–228.

Tjellström A (1989). Osseointegrated systems and their applications in the head and neck. *Adv Otolaryngol Head Neck Surg* **3:** 39–70.

Tjellström A (1990). Osseointegrated implants for replacement of absent or defective ears. *Clin Plast Surg* **17:** 355–359.

Tjellström A, Granström G (1994). Long-term follow-up with the bone-anchored hearing aid. A review of the first 100 patients between 1977 and 1985. *ENT J* **73:** 112–114.

Tjellström A, Granström G (1995). One stage procedure to establish osseointegration. A zero to five years follow-up report. *Am J Otolaryngol* **109:** 593–598.

Tjellström A, Håkansson B (1995). The bone-anchored hearing aid. Design, principles, indications and long-term results. *Otolaryngol Clin North Am* **28:** 53–72.

Tjellström A, Rosenhall U, Lindström J, Hallén O, Albrektsson A, Brånemark PI (1983). Five-year experience with skin-penetrating bone-anchored implants in the temporal bone. *Acta Otolaryngol (Stockh)* **95:** 568–575.

Tjellström A, Yonchev E, Lindström J, Brånemark PI (1985). Five years' experience with bone-anchored auricular prostheses. *Otolaryngol Head Neck Surg* **93:** 366–372.

Tolman DE, Desjardins RP (1991). Extraoral application of osseointegrated implants. *J Oral Maxillofac Surg* **49:** 33–45.

Triplett RG, Schow SR, Laskin DM (2000). Oral and maxillofacial surgery advances in implant dentistry. *Int J Oral Maxillofac Implants* **15:** 47–55.

Urken ML, Buchbinder D, Weinberg H, Vickery C, Scheiner A, Biller HF (1989). Primary placement of osseointegrated implants in microvascular mandibular reconstruction. *Otolaryngol Head Neck Surg* **101:** 56–73.

Van Oort RP, Reintsema H, Dijk G, Raghoebar GM, Roodenburg JLN (1994). Indications for extra-oral implantology. *J Invest Surg* **7:** 275–281.

Watson RM, Coward T, Forman GH, Moss JP (1993). Considerations in treatment planning for implant-supported auricular prostheses. *Int J Oral Maxillofac Implants* **8:** 688–694.

Weischer T, Mohr C (2000). A new application for craniofacial implants. *Int J Prosthodont* **13:** 108–111.

Weiss DD, Pribaz JJ, Eriksson E (1998). Nasal defects: treatment options. In: Brånemark P-I, Tolman DE, eds. *Osseointegration in craniofacial reconstruction*. Quintessence Publishing Co,: Chicago, IL, pp. 155–177.

Westin T, Tjellström A, Hammerlid E, Bergström K (1999). Long-term study of quality and safety of osseointegration for the retention of auricular prostheses. *Otolaryngol Head Neck Surg* **121:** 133–143.

Wilkes GH, Wolfaardt J (1994). Osseointegrated alloplastic versus autogenous ear reconstruction: criteria for treatment selection. *Plast Reconstr Surg* **93:** 967–979.

Wilkes GH, Wolfaardt J (2000). Prosthetic reconstruction. In: Coleman JJ, Wilkins EG, VanderKam VM, eds. *Plastic surgery; indications, operations, and outcome*. Head and neck surgery, Vol. 3. Mosby: St Louis, MO, pp. 1583–1609.

Wolfaardt J, Gehl G, Farmand G, Wilkes G (2003). Indications and methods of care for aspects of extraoral osseointegration. *Int J Oral Maxillofac Surg* **32:** 124–131.

Wolfaardt J, Wilkes G, Granström G, Bergström K (2005). Craniofacial reconstructions. In: Brånemark P-I, ed. *The osseointegration book. From calvarium to calcaneus*. Quintessence Publishing Co.: Chicago, IL, pp. 387–418.