Biomaterials in skull base surgery

Abstract

Reconstruction materials and techniques for the base of the skull have undergone rapid developments and differentiation in recent years. While mostly autotransplants, collagens or resorbable alloplastic materials are preferred for duraplasties, pronounced organ-specific differences can be observed in the reconstruction of hard tissues. The use of polymethylmethacrylate bone cement, once widespread, has decreased greatly due to the release of toxic monomers. Bony autotransplants are still used primarily for smaller skull-base defects, intraoperatively formable titanium nets may be also used for larger fronto- or laterobasal reconstructions of bony defects. Defects in visible areas are increasingly closed with preformed titanium or ceramic implants, which are planned and fitted to the individual patient using preoperative CT imaging. At the skull base, this applies especially to reconstructions of the frontal sinus. For extensive reconstructions of the orbita, titanium nets and non-resorbable plastics have proven valuable; in closing smaller defects especially of the orbital floor, resorbable implants based on Polylactin 901 are also used.

Keywords: computer assisted surgery, orbital reconstruction, skull base reconstruction, prefabrication

1 Introduction

The diagnostics and therapy of traumatic and tumor diseases of the skull base have undergone considerable change in the past 20 years. This is due to several factors which are a common basis of progress in medical techniques. The modern imaging procedures computer and magnetic resonance tomography (CT/MRT) are now indispensable to diagnostics and enable non-invasive millimeter-exact and three-dimensional depiction of all bones and soft tissues, whereas only a quarter of a century ago, complicated X-ray and layered recordings were required in order to obtain even two-dimensional images of shifts in prominent bony structures. This means that pathological processes become much clearer for the diagnostician and skull base surgeon right at the start of therapeutic considerations, which in turn enables early decisions concerning therapeutic strategy, including an estimation of interactions to be anticipated with vital and functionally-relevant neighboring structures. Where surgeons earlier had to create three dimensional images virtually in their own heads based on layered images of different projections, taking the complicated anatomy of the skull base into account, it is possible these days thanks to 3D imaging to depict and simulate existing defects, or defects which result from an intervention. This permits a much clearer idea of what a reconstruction must look like to be as near to the original as possible, and the reconstruction in turn can be created with a virtual computer-generated model, or supplemented in a real prefabricated model. This enables more aggressive surgical intervention and an expansion of therapeutic possibilities in large expansile processes which used to be incurable.

However, not only the technical possibilities of imaging, the surgical instruments and microscopes and model generation have changed, but also the materials which are available for reconstruction. Only a few decades ago, reconstructive measures were performed mostly with autogenic or allogenic material obtained from cadaver tissue, or with xenogenic material. The disadvantage was that the possibilities for autogenic tissue substitution are limited in quantity and that allogenic and xenogenic materials are coupled with the risk of disease transmission. Thus, the development of alloplastic materials was a great advance, since these are available in large quantities and are sterile. These days, a vast number of materials or material composites is available in various application forms. This has given rise to numerous experimental and clinical studies which often come to different conclusions concerning which material is best-suited for soft or hard-tissue reconstruction. The difference results from varying study designs, measuring procedures and queries.

In a thorough overview article, Potter and Ellis specified the general conditions which must be demanded of any biomaterial [1]. Among these are operative factors like sterilizability and ease of use, as well as interactions with the recipient tissue, such as biocompatibility including a lack of toxicity, allergizing and carcinogenicity. It must be noted that there is no such thing as the ideal biomaterial for skull base reconstruction. Rather, the prerequisites to be stipulated for a material depend on the localization and relationships to neighboring structures, as well as on the size and type of defect. Basically,
determination must be made between hard-tissue and soft-tissue defects which are to be covered by biomaterials. Duraplasty plays an outstanding role in the latter. Special prerequisites apply in the orbita due to the complex anatomical and functional relationships, and will for that reason be discussed in a separate chapter in this treatise [1].

2 Dura reconstruction

2.1 Principles, systematics and operative implications

Reconstruction of the dura is regularly indicated especially in frontobasal, tumor-surgical, traumatic, or iatrogenic-accident-induced defects, in order to prevent infections from arising [2]. The access to the dura can be transnasal, transfacial (Killian or spectacle incision) or transfrontal-extra or intradural (bow incision), depending on the localization and extent of the lesion, whereby the transfacial incision is decreasing greatly in use since, in addition to cosmetic detriment, it also offers greatly reduced vision compared to the bow incision [3]. By comparison, the cosmetically-favorable endonasal access is used particularly in lesions of the ethmoid bone, the sphenoid bone sinus and the Lamina cribrosa [3], [4], [5] and, performed by an experienced surgeon, brings long-term convincing results with a success rate of about 95% in a single procedure [2], [5].

The first successful surgical dura closure is attributed to Dandy; he performed an autogenic fascic transplantation in 1926 [6]. The search for the ideal material to attain both optimal prevention of liquor leakage and minimal risks had begun as early as the end of the 19th century. In his overview, Maher [7] describes trials with rubber, gold and other metal foils, and with several organic substances like human amnion membrane, chicken egg membrane, and bovine allantois, which were later abandoned because of immunological complications and foreign-body reactions.

In addition to autogenic material (depending on access and technique galeaperiostium, mucosal perichondrium and/or Fascia lata or temporalis fascia), allogenic, xenogenic or alloplastic materials can be used and affixed by dura suture or suture-free with fibrin glue. Due to the narrow path of access, easy formability is still desirable from the endonasal surgeon’s point of view; in addition, biocompatibility and stability against pressure from the brain and liquor and water impermeability are absolutely mandatory [8]. The advantages and disadvantages of the different materials must then be critically weighed against one another.

Placement of the transplant can be made in underlay-technique (between dura and bone), in overlay-technique (between bone and mucosa), or in the sandwich-technique (the two procedures simultaneously) [2], [4]. In addition, stabilization is made with fibrin glue [4]. In order to guarantee the greatest possible safety in prophylaxis against dura failure and fistula, a multi-layer closure with reconstruction of both the connective tissue level (dura) and of the mucosa should be preferred over the pure overlay or underlay technique [9], for example using the sandwich technique (Figure 1, Figure 2) and additional free or stemmed prediced mucosa flaps [2], [8].

2.2 Autogenic material

In principle, the use of the patient’s own material is usually preferred (wherever permissible for cosmetic and morbidity reasons), since it is accompanied by no risk of transmitting viral infection or the onset of foreign-body reactions, and because it is immunologically unproblematical [2], [7], [8], [10]. Moreover, the use of non-autogenic transplants, unlike autogenic transplants, is limited by the size of the defect to about 10 cm² [9]. Especially in modern minimally-invasive endonasal access, however, there is only a small quantity of connective tissue available compared to the bow incision in particular. Thus, either a second access (for example on the thigh to harvest Fascia lata), or the use of foreign material is plausible. Harvesting autogenic material may be associated with an additional intervention accompanied by corresponding morbidity or cosmetic disfigurement [10].

2.3 Allogenic and xenogenic material

Allogenic materials (such as freeze-dried “lyophilized” dura) are basically associated despite of testing of potential donors with a risk of infection with viruses (slow virus), which cannot be ruled out. In a literature analysis, Seidl [9] describes more than 50 reports of transmission of a Creutzfeldt-Jakob infection via lyophilized dura up to the year 2000! Lyophilized dura has therefore hardly been used in the past decade [3]. The use of xenogenic pericardium sterilized with γ-rays (Tutoplast Perikard®), which supposedly has a lower probability of slow-virus infection than material harvested from the dura [11], cannot completely abolish a residual risk. Both foreign body reactions and aseptic meningitis have been discussed in the use of bovine pericardium, as has the potential transmission of BSE [7].

Collagen fleece, usually of xenogenic origin (for example porcine collagen) is among the best-known natural materials. It is affixed with fibrin glue or available industrially coated with human fibrinogen and bovine (TachoComb®) or human (TachoSil®) thrombin. Fibrin polymerization is initiated in TachoComb® on contact with water, liquor or blood [12]. After a temporary closure has been achieved with fibrin, fibroblast immigration begins, which grows through the collagen in the TachoComb®-Vlies, thus effecting a definitive closure of the subarachnoid space [12]. Uncoated collagen fleece, too, possesses hemostyptic properties and can be used in support of dura closures. In neurosurgical literature, Narotam [13] reports excellent anti-liquor leakage with collagen, associated with only slight and clinically asymptomatic epidural fibrosis. The biocompatibility of the collagen, which is resorbed within
Figure 1: Schematics of dura defect covering using the sandwich procedure. The alloplastic material is affixed with fibrin adhesive in an underlay procedure between the dura and bones and as a second layer overlaid on the bone. Additionally, nasal concha mucosa is placed over this (from Arndt et al. [8]).

Figure 2: Intraoperative situs before and after covering the dura defect. a: The left image shows exuding fluorescein (arrows) under blue-light filter, which was applied translumbar for localization diagnostics of the defect. b: In the right image, the defect has already been closed in the sandwich procedure (arrow: Ethisorb®); the conchal mucosa has not yet been applied (modified and supplemented from [8]).

a few weeks, is excellent and its use can also be theoretically justified in that dura consists primarily of Type 1 collagen [7]. Collagen also possesses only weak immunogenic properties [7], [12]. In an animal collagen experiment, Zerris [14] could demonstrate that fibroblast structuring may be different even after 6 months, depending on the origin (bovine achilles tendon, bovine pericardium or bovine fetal skin), the form of denaturing, the diameter of the pores (in relation to the fibroblasts) and the thickness of the collagen (0.4–3.0 mm); independent of this, he observed in all animals completely seepage-free dura closure and clinical well-being of the test animals.

Aletsee [3] describes the use of TachoComb® in patients with frontobasal reconstruction, which had already reached a frequency of more than 80% at the Würzburg ENT-clinic in 1999. Clinically, a team in Lithuania successfully demonstrated the practical relevance of TachoSil® in a comparative prospective study of patients in whom pituitary adenomas were resected [15]: 58 patients presented with intraoperative liquorreha, in 29 of whom duraplasty was performed using autologous bone and fat, and in the other 29 with fat, cellulose and TachoSil®. In the first group, the postoperative complication rate was more than 40% and the frequency of liquor fistulas 10%. In the group with TachoSil®, the complication rate was 14%, and not one liquor fistula was observed [15]. Due to their broad and standardized use and acellularity, collagen fleeces are in a special category despite their allogenic or xenogenic origin, since the risk of transmission of pathogens appears to be minimal, but cannot be completely ruled out. For this reason, a number of clinical studies and basic articles have been published in recent years which address the use of alloplastic materials for dura reconstruction.

2.4 Alloplastic material

Alloplastic implants have the advantage of complete sterility. Basically, differentiation is made between resorbable and non-resorbable materials [10]: resorbable transplants act as a guiderail, along which enzymatic degradation occurs and which is successively replaced by immigration of endogenous connective tissue cells [10]; non-degradable material, by contrast, is covered by a connective tissue layer and embedded in this - prerequisite is, however, biocompatibility. Among the resorbable materials are pure and composite forms of Polyglyactin 910 (Vicryl®, Ethisorb®, Ethisorb Durapatch®), non-
resorbable are, for example, nylon, Dacron, silastic and a composite of the last two substances named. How are biocompatibility and integration capacity of alloplastic biomaterials to be assessed? Even though some groups have reported good results and minimal foreign-body reactions with non-resorbable materials in animal trials, inflammatory and bleeding complications have also been observed [7]. Recently, however, there was a report on a polytetrafluorethylene (PTFE)-composite specially coated with fluoropolymer, in which the polymer layer supposedly improved the liquor-antileak sealing of the PTFE-foil [16]. Intraoperative, the material was found easy to work with and an irreversible complete dura closure could be achieved in over 90% of the 119 patients in the first intervention. Despite these good results, which were comparable to the success achieved by Draf and Schick [4], the majority of literature reports address studies with resorbable collagen-based materials. Resorbable substances like poly-P-dioxanon (PDS®) and Polyglactin 910 (Vicryl®), their two-component composite (Ethisorb®), and a variant of which is additionally laminated one-sided with poly-P-dioxanon (Ethisorb Durapatch®) are available. The function of the additional poly-P-dioxanon layer is to improve the water impermeability compared to pure Ethisorb®. Moreover, Ethisorb® and Ethisorb Durapatch® have the advantage over Vicryl® that they consist of materials with differing resorption times: the time for Vicryl® is 45–60 days, for PDS® 90–180 days, which renders degradation incremental and prolonged [9]. In a clinical study, Arndt [8] demonstrated that Ethisorb® and Ethisorb Durapatch® can be easily modelled intraoperatively, Seidl was able to prove in 51 frontobasis defects in 45 patients closed primarily in the sandwich technique via different access pathways that the Ethisorb® clinically prevents liquor leakage and is not associated with apparent local or systemic toxicity [9]. Seidl [9] suggested as a plausible advantage over autogenic transplants that polyglactin and poly-P-dioxanon show no tendency to local shrinkage and can thus bridge the phase to complete integration. For example, unlike collagen fleece, autologous connective tissue may shrink up to 30% [4]; this means that local rebasing and thereby brain and dura mobilization must be performed on a broader scale if an autotransplant is used. However, Draf assumes that infection cannot be completely ruled out even in (allo- or xenogenic) collages and thus recommends exclusive use of fascia as “autologic collagen” [4]. Schick [10] investigated fibroblast activity and dura cell migration using various closure materials and demonstrated a basic immigration of fibroblasts to resorbable non-autologous transplants, whereby the activity with poly-P-dioxanon (PDS®) was lower than with collagen. In addition, there is an interesting observation in experiments showing that collagen or PDS® can induce greater fibroblast activity than autogenic bradytrophic tissue like cartilage [10]. The same team [17] was able to prove in a cell-culture model that the application of fibrin glue to porcine dura is already sufficient to induce germination of the fibroblasts starting at the edge of a defect and completely grow over a central defect 2 mm in diameter. They also observed fibroblast growth along a Vicryl® mesh. In considering frontobasis reconstruction, attention should be paid not only to the major aspects of closing the dura defect, but also to the fact that the procedures cited do not imply reconstruction of the bony protection. However, there is evidence that when biomaterial is introduced, the bony frontobasis can also be stimulated to osteoneogenesis. In culture models, Arndt [18] and Itthichaisri [19] investigated the proliferation rates of osteoblast-like cells (HOB-like cells) after application to various biomaterials. The greatest activity was observed in the cell proliferation test in contact with Ethisorb®; by contrast, the proliferation rate in contact with PDS® was ten times lower. Even lower activity of the HOB-like cells was observed after application to fibrin glue (Beriplast®). These results are relevant not only in the aspect of active bone growth after dura closure, but especially in the aspect of preoperative tissue culture prior to skull base closure. Wolf [17] observed that germination of fibroblasts along a polyglactin-(Vicryl®-) mesh was potentiated after application of the growth factor FGF (fibroblast growth factor). This widens the perspective of optimal preoperative preparation for closure of hard and soft tissue defects by tissue engineering using autogenic and alloplastic materials. This aspect becomes even more attractive in light of considerations by the team headed by Schick and Wolf [17]: the possibility of harvesting autologous fibroblasts from the patient himself and of generating fibrin glue from the patient’s own blood, means it may be possible to dispense with any potentially viral-infectious contaminated material.

3 Hard tissue replacement

3.1 Principles, systematics and operative implications

The reconstruction of hard tissue (skull cap, skull base, orbita boundaries) is undertaken for vital (protection), functional (e.g. vision), and also cosmetic reasons. Differentiation between the materials available for reconstruction is based on the one hand on the material group of which the transplant or implant consists, and on the other on the strategy necessary in planning the intervention (preoperative patient-specific conditioning/production or intraoperative modeling of the implant). The principles and use of allogenic and xenogenic materials are described in the article by Neumann, Chap. 3.2 (http://www. egms.de/en/journals/cto/2011-8/cto000060.shtml); compared to duraplasty, these play a subordinate role in hard-tissue replacement in mid-face, so that the decision usually falls between autogenic and alloplastic materials. Several product groups are available among the latter, with a nearly limitless number of individual substances and products.
Which biomaterial in which method (intra- or preoperative modeling) is to be used in the reconstruction must already be discussed and decided in planning the procedure. Several aspects must be taken into consideration. These include the indication for the procedure (reconstruction during or after a tumor disease?), the potential necessity of intraoperative change in decision and remodeling, the position of the implant in relation to its surroundings (contact with mucosa?), and the complexity of the procedure (solely hard tissue or combined hard and soft tissue reconstruction?).

When a tumor disease is present, great value is of course placed on the possibility of long-term, high-quality imaging for early recognition of recurrence. If the implant lies directly on a mucosal surface, bacterial affection must be expected both intraoperatively and under long-term aspects, to which the implant must be adapted. In simultaneous dura reconstruction the question arises, which of the materials used for hard-tissue reconstruction have a positive influence on the integration of the dura reconstruction or at least the lowest negative influence. Important properties of some of the material groups are listed in Table 1. Chapter 3.1 of the article by Neumann (http://www.egms.de/en/journals/cto/2011-8/cto000060.shtml) gives details concerning the reactions of bones in the presence of implants, including under the aspects of integration, porosity, infection risks and infection prophylaxis. Since an elevated risk of implant infection must be anticipated at the skull base in the immediate vicinity of the sinuses [20], [21], most authors recommend peri- and postoperative antibiotic prophylaxis, even if there are no preoperative signs of wound infection.

3.2 Autogenic material

Autogenic material is available only for smaller defects and in limited quantities, and can moreover only be modeled to a limited extent. In small skull base defects (e.g. boney ethmoidal roof and olfactory channel), a split transplant of the Tabula externa cap is made to protect the duraplasty; if cranialization of the frontal sinus is made via a transfrontal bow incision, the resected posterior wall may function as the donor organ (if it is preserved to a usable extent and is permissible with respect to the underlying disease). If larger defects must be closed or if complicated modeling is required (e.g. in reconstruction of the orbita), the functional usability of such autogenic transplants is limited. Moreover, the autoreabsorption rate (which may include complete loss of the transplant) cannot be predicted in bone transplantations [22], [23].

3.3 Alloplastic material

Basically, alloplastic materials for hard-tissue replacement are divided into several categories: based on their composition (metals, ceramics and cement), their resorbability and based on the possibility of preforming or intraoperative modeling.

3.3.1 Metal implants

In this group, titanium has largely replaced steel and other metals thanks to its good biocompatibility. The surface converts to titanium oxide and is thus extremely corrosion resistant. The chemical and mechanical properties of titanium and aspects of biocompatibility and possible tissue reactions are discussed in detail in Chapter 2.2 of the article by Neumann (http://www.egms.de/en/journals/cto/2011-8/cto000060.shtml). Titanium implants are basically available in two forms: intraoperative moldable meshes of various strengths and mesh thickness, and as plates which are produced preoperative and patient specific.

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**Table 1: Properties of Materials for Hard-tissue Reconstruction (modified from Eufinger et al. [22] and Peltola et al. [38])**

| Material              | Biocompatibility | Costs          | Stability      | Intraoperative Processing |
|-----------------------|------------------|----------------|----------------|---------------------------|
| Autogenic bones       | very high        | none or low    | doubtful (resorption?) | easily possible         |
| Alloogenic bones      | high             | low            | doubtful (resorption?) | easily possible         |
| Acrylic bone cement   | moderate         | low            | can break      | easily possible         |
| Hydroxyapatite        | high             | moderate       | can break      | moderate or easy*       |
| Polyethylene          | high             | moderate       | moderate       | moderate**               |
| Titanium mesh         | high             | moderate       | moderate       | moderate**               |
| Preformed titanium plate | high         | high           | very high      | impossible              |
| Preformed glass ceramic | high          | high           | high, can be breakable | low                     |

* depending on product and form (granulate, plate); ** depending on thickness
3.3.1.1 Titanium mesh

Titanium mesh can be formed individually intraoperatively and is suited for the reconstruction of smaller defects. For this reason, it is often used in the frontal and orbital area, as well as in the ethmoidal roof (Figure 3, Figure 4) and in laterobasal procedures to prop the temporal lobe to the Fossa infratemporialis (Figure 5) or to the jaw joint [23], [24]. If the reconstructive procedure is made under computer-assisted conditions, a virtual model on which to base preforming of the mesh can be created preoperatively using reflective software for optimal forming of the mesh and improvement of the reconstruction results (if the original contours of the area to be reconstructed can no longer be precisely recognized due to trauma or tumor) [24], [25]. Intraoperative registering of the patient can be made invasively or non-invasively using a dental splint to prevent an additional lesion [26], [27]. Intraoperative, fine adaptation can be made to the mesh based on the local conditions and on the original and imaged layers projected in the navigation system [25]. Postoperative analyses have revealed precision in bony computer-assisted reconstruction of 0.5–3 mm in the orbita and 1.5–6 mm in mid-face azygoma and zygoma, and a skin surface asymmetry of 0.6–2.9 mm [28]. However, even with intact skin coverage, transmigration of the mesh has been observed, especially in critical areas like the medial angle of the eye. In addition, there is hinderance of MR-tomographic diagnostics, albeit to a small degree in the case of thin mesh (Figure 5) [23]. Pathogenesis, incidence, consequences and possible alternatives for prophylaxis of infection of titanium implants, which occurs occasionally, are discussed in detail in Chapters 2.2.3, 2.2.5 and 2.4 of the Neumann article (http://www.egms.de/en/journals/cto/2011-8/cto000060.shtml) and are therefore not repeated here.

![Figure 3: Sagittal CT of a paranasal sinus carcinoma with destruction of the rhinobase, dura infiltration and elevation of the frontal brain.](Image)

3.3.1.2 Titanium blocks

Eufinger [22] assumes that intraoperative modeling of whatever material (titanium, other alloplastic or autologous substances) is unsatisfactory from a protective and esthetic point of view. With respect to protection, he ascribes this to unpredictable resorption mechanisms of autogenic bones or the low thickness of intraoperatively-formable meshes, and with respect to esthetics to intraoperative swelling and limited vision in large defects, which may confuse the surgeon. He therefore prefers preformed implants. These titanium implants are created from solid titanium blocks, 1.5 mm thick, and prefabricated individually, based on preoperative workup of a CT-dataset in which the area to be replaced is marked [29], [30]. The osteoneogenetic potency of titanium is low but can be increased by industrial modifications of the titanium surface [19]. Fitting the prefabricated titanium implant requires an adequately perfused and vital soft-tissue environment to prevent perforations through the skin or in the sinuses with a possible consecutive superinfection; if this prerequisite is not given, it must be created in a preparatory procedure in which an implant bed is prepared using, for example, a microsurgically anastomosed flap [31].

Preformed titanium implants are used especially for the reconstruction of the skull cap. In the skull base, reconstructions of frontal sinuses including their floor, but not the ethmoidal roof or infratemporal fossa, are typical localizations for their use [24]. Since infectious complications are extremely rare with titanium implants [32], their use for reconstruction after radical resection at the skull base is successful even in patients in whom multiple previous procedures and attempts at frontal sinus contour reconstruction with other bone substitutes like Palacos® were unsuccessful due to frontal bone osteomyelitis [33]. In addition to the general positive properties of alloplastic materials (no donor region and morbidity, no virus transmission), the pronounced stability is another advantage of preoperatively produced titanium implants; moreover, thanks to computer-assisted planning, it is possible to precisely recreate the destroyed contour [22]. In practice, preformed titanium implants are generated as follows [22], [34]: using a high-resolution (1 mm layers) three-dimensional CT-dataset, the bony areas to be resected are marked and recorded on a CD, which is processed by the implant manufacturer and used for millimeter-precise production of the implant (“preoperative planning surgery”). Only a few days are required for the manufacturing process, the price, in our experience, is in the 4-digit Euro range, depending on the size and material of the implant. The precision of preforming lies within the tenth of a millimeter range [29], [30]. The resection can then be undertaken in a computer-assisted procedure under navigation conditions so that the resection boundaries transferred preoperatively to the navigation dataset can be precisely maintained; as an alternative, a so-called resection template can be obtained from the manufacturer which precisely reflects the contours of the actual implant [29], [30].

Long-term studies on several hundred patients have shown that, despite the objectively lower complication rate, some patients developed psychological difficulties with the large metal foreign body or – due to the good temperature conduction of the titanium – hypersensitivity to cold and (to a lesser extent) heat [34], [35]. A further
The disadvantage of the preformed titanium blocks is their unsuitability for intraoperative reworking: if the contours are not in exact agreement or should intraoperative findings reveal a possibility of resecting a smaller bone area, for example in tumor operations, the bone resection demanded by the actual implant still must be undertaken [23]. A postoperative problem of thick titanium implants is their property of generating artifacts in imaging procedures, which reduces the sensitivity of MR-tomography in tumor diagnostics and postoperative care [23] and overradiation artifacts in the CT [36]. However, quenching in the MRT can be reduced by suitable spin frequencies [36].

### 3.3.2 Non-metallic implants

#### 3.3.2.1 Ceramics

Ceramics are non-metallic anorganic substances which are produced and given fixed forms under very high temperatures. See Chap. 3.3.2.1 in Neumann’s article (http://www.egms.de/en/journals/cto/2011-8/cto000060.shtml) for the history and early experiences with ceramics.

Bioactive glass ceramics are based on silicon-aluminum oxide phosphate and have an active surface on which osteoneogenesis can be induced by interaction with osteoblasts [37]. They are industrially available as a granulate or in blocks like Bioverit® and bind chemically to surrounding tissue by elution and solution of ions [36]. Glass ceramics have excellent biocompatibility, osseointegration and very slow degradation – if at all – is discussed [37], [38]. In animal experiments, a calcium phosphate-rich layer could be observed between bone and Bioverit®, which indicates a chemical binding [39]. Glass ceramic granulate can be introduced intraoperative in the required quantity and then bound with saline solution. Its use is thus more variable than plates or blocks which must be formed preoperatively [37]; however, the latter are suitable for implants preformed pre-
operative based on virtual models [40], [41]. Heat conduction is considerably lower than for titanium and artifacts in imaging are avoided [40]. In a clinical study, Aitasalo demonstrated that glass ceramics are well-suited for frontal sinus obliteration and orbita reconstruction: none of his 65 patients suffered inflammatory or granulomatous complication [37]. Siebert published similar positive experience using 25 preformed Bioverit II implants [40]. Aitasalo attributed the good results to, among other things, the experimentally-proven antibacterial properties of glass ceramics (especially against gram-negative pathogens [42]) [37]. These ceramics also have a not unfavorable influence on the phagocytosis capacity of leukocytes [43]. The bone osteoneogenically induced by glass has also been found to be more similar to natural frontal bone than bone induced by means hydroxylapatit [37]. In orthopedic literature, osteoneogenesis with consecutively better embedding and shear-strength stability of glass ceramic (Bioverit I®)-coated than uncoated hip prostheses is also reported [39].

In the skull base, experience has been gained with ceramics especially in frontal sinus obliteration and reconstruction [37], [41], as well as the orbita (see Chap. 4.3). Figure 6 and Figure 7 show the procedure in planning and fitting of preformed glass ceramics using the example of a woman with fibrous dysplasia.

If ceramics are planned preoperative and patient-specific, the same principles with respect to modalities to be heeded apply for the preoperative planning surgery as discussed above for titanium [41]. However, glass ceramics have the advantage over titanium that slight deviations between the planned and prefabricated form and the intraoperative requirements can be corrected, at least to a small extent.

3.3.2.2 Cements

Cements are anorganic non-metallic substances which harden under the influence of a binder. Polymethylmethacryl-(PMMA-) bone cement (Palacos®) is probably the alloplastic foreign material most frequently used in the decades in which skull base reconstructions have been performed [23], [44]. A great advantage of acrylic cement is its excellent intraoperative formability [23]. In cell cultures, it does lead to greater osteoblast activity than titanium or hydroxylapatit [19], which permits the assumption of better osseointegration, but this activity is slight compared to that induced by polyglactid (Vicryl®/Ethisorb®). However, PMMA cement is not resorbable and releases monomers into the environment due to the high temperatures which arise intraoperative in polymerization. This reduces its biocompatibility and can lead to local and systemic toxic reactions [22], [23]. In addition, infections on contact of the cement with the nasal sinus have been reported [23].

The stability of the cement can be influenced intraoperatively by the mixing method: cement mixed under vacuum shows greater flexural strength than hand-mixed, probably due to a reduction of air bubbles formed [45]; on the other hand, a high antibiotic additive (by the manufacturer) in the cement and blood contamination reduce its stability. With respect to stability, however, great differences have been observed between various products and manufacturers of PMMA cement [46]. In principle, PMMA-based implants can also be preformed (see Neumann, Chap. 3.3.3.1, http://www.e homeless.de/en/journals/cto/2011-8/cto000060.shtml), but they have not yet supplanted ceramics and titanium in this form [40].

Due to the local and systemic toxic effect resulting from the release of monomers, a search has been conducted in recent years for similarly simple alternatives. In principle, hydroxyapatit cement (BoneSource®) can also be used for hard tissue reconstruction and frontal sinus obliteration. The basis is a calcium phosphate compound similar in its synthetic form to the natural variant present in bones [37], See Neumann, Chapt. 3.3.2.2 (http://www.e homeless.de/en/journals/cto/2011-8/cto000060.shtml) for information on chemical properties, systematics and history of calcium phosphate. Apatit has very good biocompatibility, especially because the heat typical of PMMA cement does not arise during the application. In addition, hydroxylapatit cement has the advantage that it can be prepared intraoperative as needed, since it is available as a powder which can be mixed intraoperative with a saline solution, applied in a patient-specific adequate quantity and formed, then hardens in less than 30 minutes [37]. As with glass ceramics, binding between the surface and neighboring soft tissue occurs via the formation of collagen fibers [37] and leads there to osteoneogenesis. In an animal experiment, Dost and his colleagues demonstrated osteoneogenesis in the middle ear, using bioactive ossicle prostheses made of hydroxyapatit, glass ceramic (Ceravital®), or biovitroceramic (Bioverit II®) [47]. The osteogenetic potency of apatit (BoneSource®) is, however, lower than that of Ethisorb® in the culture model [19]. Hydroxyapatit is also breakable and tends to fragmentation. The stability is thus not uniformly reported in the literature. Whereas Aitasalo [37] published relatively good clinical results for glass ceramics, other teams observed a lack of long-term stability in larger bone defects [48], [49]. Brushit (chronOS®Injekt), which also contains calcium phosphate also did not achieve adequate stability for larger defect reconstructions due to slow osteoneogenesis with equally rapid degradation of the implant material [50].

When used near mucosas, apatit is associated with an elevated risk of chronic infections [23] and is thus not without controversy concerning the potential occurrence of inflammatory processes (sinuses, laterobasis near the ear) [49].

Glass ionomer cement, which was a common material in the reconstruction of frontobasis and frontal sinus, is no longer used for skull base reconstruction due to reports of serious complications, like aluminum encephalopathy [51], [52].
3.3.2.3 Composite implants

Composites of various basic materials represent advances in the development of preformed implants. Experience has been gained in skull base reconstructions with composites of carbon-fiber polymers and an epoxy resin matrix (CFPE). CFPE implants are biocompatible and are not degraded but encased in newly-formed layers of connective tissue [53]. They are lighter than metal implants, can be worked up intraoperative to a limited extent and do not present with metal-typical artifacts in imaging examinations [53], [54]. Problem-free postoperative radiation therapy is possible [54]. In a study of 29 patients with defects in the cranial skull and frontal facial skull years, Saringer did not observe any inflammatory, local or systemic-toxic reactions over a period of more than 3 years; none of the 29 CFRP implants had to be explanted [53]. No extensive data are available for the skull base in the narrower sense (ethmoidal roof, laterobasis).

A multi-layer implant, consisting of three different polylactide polymers processed with amorphous calcium phosphate (ACP) and calcium carbonate to a five-layer composite, were developed by a team in Bochum [35], [55]. In the core come first porous, easily degradable layers which are intended to promote osteoblast immigration and neogenesis of bone from the dura. These are followed to the outside by increasingly stable, slow-degrading layers which render long-term protection. The pore size of the inner layer is 200–400 µm and was associated in cell cultures and animal experiments with biocompatibility and high osteoblast activity [55], [56], [57]. ACP has osteoneogenetic potency and contributes to the fact that the pH course of the implant remains nearly constant in the physiological range for 28 days [58], [59]. Correspondingly, new bone formation proceed-
ing from the dura could be observed in animal experiments after several months, as well as a bony growth through the crevices between implant and resection edge, coupled with bony replacement of the outer implant layer over a year. However, if the contact to the dura with its osteoneogenetic potency is impaired (e.g. during simultaneous duraplasty or due to hemorrhage), irregular degradation of the inner layer, fragmentation and partial dislocation may occur, as Eufinger observed in one of his test animals [35]. Further examples of the composition and use of composites are given in Chap. 3.4 of the Neumann article (http://www.egms.de/en/journals/cto/2011-8/cto000060.shtml).

3.3.2.4 Plastics

High biocompatibility is ascribed in the literature to porous polyethylene (Medpor®) [23]. It has pores of 150–250 μm, a size suitable for the immigration of autologous connective tissue cells, it can be formed intraoperative to a moderate extent [23], [58] and is not relevantly resorbed. However, foreign body giant cells are found histologically in the surroundings which contain the material, so at least minimal degradation must be assumed [60]. It is encased by a connective tissue membrane: encasing and cell immigration thus contribute to stabilization of the implant, in supplement to the titanium screws with which it is customarily affixed [60]. Due to the limited formability and limited shock stability, this material is only suitable for smaller defects, since it cannot compete in the same category with individually preformed implants and the possibility they offer with respect to contouring and shock resistance. Gosau [60] had to remove the implant in two of his 27 patients due to infections conducted to the upper jaw, which reveals the problems in use near potentially infectious organs (teeth, sinuses). Moreover, polyethylene implants have the disadvantage that they cannot be visualized in conventional X-rays and only poorly in the CT. However, they do not induce artifacts to the same extent as titanium in the MRT [23], [39]. By contrast, positive experience has been reported in orbita reconstruction (see Chap. 4.3). Frodel [23] discusses polyetheretherketone (PEEK) as an alternative to titanium and polyethylene: this has greater biocompatibility than polyethylene with the advantage of individual preformability (like titanium), but it is lighter than titanium, can be processed intraoperative at least to a limited extent and is not associated with the artifacts typical of titanium in the MRT; however, like polyethylene, it is poorly imaged in the CT.

4.1 Principles, systematics and operative implications

Due to the functional importance, beyond the esthetic importance of this central facial area as a communication medium, reconstruction of the orbita makes higher demands on symmetry and axial precision than reconstruction of the skull cap and the zygoma. This involves on the one hand the vertical height of traumatically or tumor-related destruction of the orbita axis, on the other also its rotatory position. If, in addition to the particularly esthetically disruptive ex- or enophthalmus, reconstruction of the axial orientation and pre-tension of the straight eye muscles is unsuccessful, vertical or rotatory-induced double-vision results, depending on the primary localization and components of the damage, which must be corrected in a secondary procedure. The latter involves both hard tissue reconstruction and the position and possibly augmentation of the soft tissue, and fixation of the M. obliquus superior to the trochlea. The complex relationships in the orbita make it obligatory to undertake plannable procedures principally in computer-assisted modes, as long as the lesion to be corrected is expansive [25], [27]. In planning the procedure, this enables determination not only of the size and form of the implant, but also the desired position in the orbita, which can be marked in preparation of the intraoperative application [61]. The orbita must always be considered as a three-dimensional system, so that one-dimensional parameters for correction analysis, such as Hertel index (computed tomographic shift of the corneal surface in relation to the lateral orbita ring) are not sufficient; this does not correctly define the extent of malpositioning in lateral orbita-wall fractures [25].

Lesions in the orbita floor area account for about two-thirds, and are thus the most common fractures of the orbita; if the medial orbita wall is also affected, the probability that double vision will occur is higher and a physiologically adequate reconstruction more difficult [32], [62]. Due to the discussed sensitivity of the orbita and its soft-tissue contents to even slight impairments, the principles defined by Ellis [32] concerning the use of a material in this region must be especially heeded: the material must be biocompatible, it may not be toxic, allergizing or carcerogenic, it should be easy to apply, stable over long periods and still be easy to cut, form and adapt without “memory” properties once the procedure is completed, it must be sterilizable without chemical transformation, it may not promote the growth of microorganisms and should be visible in imaging procedures.

4.2 Autogenic material

The use of autogenic bone – once the gold standard in orbita reconstruction [1] – is no longer the material of first choice for attaining a functionally long-lasting successful orbita reconstruction due to potential donor morbidity and since the extent of resorption cannot be predicted. This applies particularly for secondary correction in chronic orbita defects [32], [63]. Autogenous cartilage [64] may be suitable at best in selected patients with very small defects [1]. According to the principles cited above, differentiation must be made between re-
sorbable and inert substances in using biomaterials in orbita reconstructions.

4.3 Alloplastic materials

4.3.1 Titanium and non-resorbable plastics

In his overview, Ellis recommends non-resorbable materials: titanium mesh for the treatment of acute injuries and porous polyethylene (Medpor®) for secondary reconstruction [32], which fulfill to a large extent the principles cited above. He states that reservations against non-resorbable materials are not justified: infection with titanium and the extrusion of an orbita floor mesh are extremely rare (compared for example with resorbable PDS®), moreover, no case of bulbus or optic nerve injury due to dislocation of a mesh after a subsequent retrauma has been reported [32], nor has any incarceration of an eye muscle in the mesh been observed. To attain adequate stability, the thickness of the titanium mesh should, however, be 0.4 mm. Like titanium mesh, which is overgrown with germinating connective tissue, porous polyethylene is penetrated by connective tissue and affixed, as long as the pore size is between 100 and 200 μm [32]. This minimizes the risk of extrusion compared to nonporous substances (e.g. silicon, Teflon) [32]. However, polyethylene cannot be imaged. Lin [65] recommends polyethylene also in the treatment of acute orbita defects, since it is easier to use than titanium and has a comparably low infection rate. Öztürk [66], Nam [67] and Yilmaz [68] also observed no wound infection with good functional results after implantation of porous polyethylene with 0.85–1.5 mm thickness. Rinna recommends rather titanium mesh for larger defects [63]. This should, however, always be embedded in well-vascularized tissue [69].

Silicon and Teflon are considered by these authors as largely obsolete in orbita reconstruction. It must be remembered with non-resorbable materials that should removal from the orbita be required after a necessary revision procedure several weeks or months after initial placement (e.g. in a secondary infection), this could be difficult due to the through-growth of the connective tissue and potentially problematic for neighboring eye muscles [65].

If a reconstructive procedure is planned with computer assistance, discussions must include whether the alloplastic material to be implanted should be formed exclusively intraoperative (titanium mesh), or whether from the start production of a preformed implant using additional preoperative computer-assisted planning surgery is desirable [70], [71]; in the latter case, however, the use of material which can be worked up to a limited degree, like glass ceramic [38], [72] or better preformed titanium mesh [71], [73] should be preferred over titanium block which cannot be altered.

4.3.2 Resorbable materials

Several authors plead for reconstruction of the orbita floor with resorbable materials with osteonegenetic potency, since they rate the infections, migrations and implant extrusions observed with non-resorbable materials as basically unsafe [62], [73], [74]. Büchel observed an implant-specific complication in three patients after treatment of 87 orbita floor fractures with Ethisorb®, namely enophthalmus and persistent double vision. In two cases, operative revision was required [75]. However, in a comparison with published results of orbita floor treatment with PDS®-Foil or non-resorbable materials, Büchel rates the probability of persistent complication requiring intervention when Ethisorb®-Foil is used as slight; however it is recommended that the use of Ethisorb®-Foil be limited to defects of maximal 2x2 cm [75]. The literature is inconsistent with respect to PDS®-Foil. Röpke recommends PDS® for fresh defects [69]. On the other hand, Baumann [76] observed enophthalmus with recurrent double vision after resorption of the foil as a late complication in the use of a PDS® implant. Thanks to the good penetrating growth and integration of Ethisorb®, this is not observed with that material [75], thus the necessity of intraoperative over-correction is not necessary in using Ethisorb®. Ellis reports that PDS®-Fools are not approved in the USA for orbita floor reconstruction [32]. Observations of greater activation of osteoblast-like cells by Ethisorb® than by PDS® in the culture model [18], [19] agree with the good results reported by Büchel after implantation of an Ethisorb-Foil® under the aspect of osteoneogenesis on the orbita floor. Smaller defects can also be closed with calcium phosphate-(apatit-) cement, which is easy to handle intraoperative, biocompatible and resorbable [77]. Injection of hydroxyapatit cement for cosmetic compensation of soft-tissue defects in patients with enophthalmus and glass eye have also been published [78]. The possibilities of in-vivo tissue engineering after experimental orbita floor resection have been investigated in animal trials, whereby significant bone growth was observed after 28 days [62]. However, especially in the area of the sensitive orbita, it must be remembered that complications caused by intolerances often do not occur until years later; Potter [1] therefore recommends critical weighing of new material reported in the many publications which have possibly been insufficiently tested for long-term tolerance over a period of decades.

5 Summarizing evaluation and outlook

The above discussion illustrates that the demands set for biomaterials differ for the individual regions and organ systems of the skull base. Especially in hard-tissue reconstruction, there is a tendency away from autogenic and toward alloplastic materials. Allo- or xenogenic materials, apart from collagen and fibrin adhesive components, are
hardly used any more. In addition to intraoperative navigation-supported formable titanium meshes for skull base and orbita reconstruction, individually preformed implants are on the increase for hard-tissue reconstruction, especially in visible areas of the skull base. There is a tendency to no longer use the titanium block implants which have dominated thus far among preformed implants. Rather, ceramics which can be formed intraoperatively at least to a limited extent are increasingly used. Non-resorbable plastics are associated with the risk of infection in the vicinity of mucosae. Nonetheless, they have proven valuable for the reconstruction of the orbita, along with resorbable implants for the treatment of smaller defects. For the future, experience with tissue engineering opens the perspective of being able to dispense with any potentially infectious material, at least for closure of smaller defects, by means of harvesting autologous fibroblasts and autologous fibrin glue.

References

1. Potter JK, Ellis E. Biomaterials for the reconstruction of the internal orbit. J Oral Maxillofac Surg. 2004; 62: 1280-1297. DOI: 10.1016/j.joms.2004.04.018
2. Castelnouvo PG, Delu G, Locatelli D, Padoan G, de Bernardi F, Pistochini A, Bignami M. Endonasal endoscopic duraplasty: Our experience. Skull Base. 2006; 16: 19-23. DOI: 10.1055/s-2005-922096
3. Aletsee C, Konopik V, Dazert S, Dieler R. Operative Versorgung von Verletzungen der Rhinobasis. Laryngoo-Rhino-Otol. 2003; 82: 626-631. DOI: 10.1055/s-2003-426868
4. Draf W, Schick B. How I do it: Endoscopic-microscopic anterior skull base reconstruction. Skull Base. 2007; 17: 53-58. DOI: 10.1055/s-2006-959335
5. Schick B, Ibing R, Brors D, Draf W. Longterm study in endonasal duraplasty and review of the literature. Ann Otol Laryngol Rhinol. 2001; 114: 142-147.
6. Dandy WD. Pneumocephalus (intracranial pneumocele or aerocoele). Arch Surg. 1926; 12: 949-982.
7. Maher CO, Anderson RE, McClelland RL, Link MJ. Evaluation of a novel propylene oxide-treated collagen material as a dural substitute. J Neurosurg. 2003; 99: 1070-1076. DOI: 10.3171/jns.2003.99.6.1070
8. Arndt S, Maier W, Aschendorff A, Klenzner T, Schipper J. Proliferation rate of human osteoblast-like cells on alloplastic biomaterials and their clinical application for the transnasal duraplasty approach. J Cell Mol Med. 2006; 10: 749-757. DOI: 10.1111/j.1582-4934.2006.tb00434.x
9. Ittichaisiri C, Wiedemann-al Ahmad M, Hübner U, al-Ahmad A, Schön R, Schmelzeisen R, Gelrich NC. Comparative in vitro study of the proliferation and growth of human osteoblast-like cells on various biomaterials. J Biomed Mat Res (A). 2007; 82: 777-787. DOI: 10.1002/jbm.a.31191
10. Brunner FX. Implantatiematerialien - was hat sich wowährt? Eur Arch Otorhinolaryngol. 1993; Suppl 1: 311-336.
11. Gürler M, Winter M. Rhinoliquorrhoe - Otoiliquorrhoe. HNO. 1998; 46: 205-219.
12. Eufinger H, Saylor B. Computer-assisted prefabrication of individual craniofacial implants. AORN J. 2001; 74: 648-653. DOI: 10.1016/S0001-2092(06)6763-8
13. Narotam PK, Reddy K, Fewer D, Qiao F, Nathoo N. Collagen matrix duraplasty for cranial and spinal surgery: a clinical and imaging study. J Neurosurg. 2007; 106: 45-51. DOI: 10.3171/jns.2007.106.1.45
14. Zerris VA, James KS, Roberts JB, Bell E, Heilman CB. Repair of the dura mater with processed collagen devices. J Biomed Mater Res (B). 2007; 83: 580-588. DOI: 10.1002/jbmb.30831
15. Tamasauskas A, Sinkunas K, Draf W, Deltuva V, Matukevicius A, Rastenyte D, Vaitkus S. Management of cerebrospinal fluid leak after surgical removal of pituitary adenomas. Medicina. 2008; 44: 302-307.
16. Messing-Jünger AM, Ibanez J, Calbucci F, Choux M, Lena G, Mohsenipour I, van Caldenbergh F. Effectiveness and handling characteristics of a three-layer polymer dura substitute: a prospective multicenter clinical study. J Neurosurg. 2006; 105: 853-858. DOI: 10.3171/jns.2006.105.6.853
17. Wolf G, Plinkert PK, Schick B. Zelltransplantationen zum Liquoristelfenschluss. Erfahrungen mit fibrinklebrigen und Fibroblasten. HNO. 2005; 53: 438-445.
18. Arndt S, Ittichaisiri C, Maier W, Gelrich NC, Schipper J. Proliferation rate of human osteoblast-like cells on synthetic biomaterials and their clinical application for the transnasal duraplasty approach. J Cell Mol Med. 2006; 10: 749-757. DOI: 10.1111/j.1582-4934.2006.tb00434.x
19. Ittichaisiri C, Wiedemann-al Ahmad M, Hübner U, al-Ahmad A, Schön R, Schmelzeisen R, Gelrich NC. Comparative in vitro study of the proliferation and growth of human osteoblast-like cells on various biomaterials. J Biomed Mat Res (A). 2007; 82: 777-787. DOI: 10.1002/jbm.a.31191
20. Brunner FX. Implantatiematerialien - was hat sich bewährt? Eur Arch Otorhinolaryngol. 1993; Suppl 1: 311-336.
21. Gürler M, Winter M. Rhinoliquorrhoe - Otoiliquorrhoe. HNO. 1998; 46: 205-219.
22. Eufinger H, Saylor B. Computer-assisted prefabrication of individual craniofacial implants. AORN J. 2001; 74: 648-653. DOI: 10.1016/S0001-2092(06)6763-8
23. Frodel JL. Computer-designed implants for fronto-orbital defect reconstruction. Fac Plast Surg. 2008; 24: 22-34. DOI: 10.1055/s-2007-1021459
24. Schipper J, Ridder GJ, Spetzger U, Teszler CB, Fradis M, Maier W. Individual prefabricated titanium implants and titanium mesh in skull base reconstructive surgery. Eur Arch Otorhinolaryngol. 2004; 261: 282-289. DOI: 10.1007/s00405-003-0686-8
25. Gelrich NC, Schramm A, Hammer B, Rojas S, Cufi D, Lagreze W, Schmelzeisen R, Gelrich NC. Computer-assisted secondary reconstruction of unilateral posttraumatic orbital deformity. Plast Reconstr Surg. 2002; 110: 1417-1429. DOI: 10.1097/00006534-20021100-00006
26. Schipper J, Maier W, Arabakis I, Spetzger U, Laszg R. Navigation as a tool to visualize bone-covered hidden structures in transfrontal approaches. J Laryngol Otol. 2004; 118: 849-856. DOI: 10.1258/0022155042703651
27. Schmelzeisen R, Gelrich NC, Schön R, Gutwald R, Zieselmann C, Schramm A. Navigation-assisted reconstruction of medial orbital wall and floor contour in crania-maxillofacial reconstruction. Injury. 2004; 35: 955-962. DOI: 10.1016/j.injury.2004.06.005
28. Metzger MC, Hohlweg-Majert B, Schön R, Teschner M, Gelrich NC, Schmelzeisen R, Gutwald R. Verification of clinical precision of the proliferation and growth of human osteoblast-like cells on various biomaterials. J Biomed Mat Res (A). 2007; 82: 777-787. DOI: 10.1002/jbm.a.31191
29. Brunner FX. Implantatiematerialien - was hat sich bewährt? Eur Arch Otorhinolaryngol. 1993; Suppl 1: 311-336.
30. Ittichaisiri C, Wiedemann-al Ahmad M, Hübner U, al-Ahmad A, Schön R, Schmelzeisen R, Gelrich NC. Comparative in vitro study of the proliferation and growth of human osteoblast-like cells on various biomaterials. J Biomed Mat Res (A). 2007; 82: 777-787. DOI: 10.1002/jbm.a.31191
29. Eufinger H, Wehmöller M. Individual prefabricated titanium implants in reconstructive craniofacial surgery: Clinical and technical aspects of the first 22 cases. Plast Reconstr Surg. 1998; 102: 300-308. DOI: 10.1097/00006534-19980800-00002

30. Eufinger H, Wittkampf AR, Wehmöller M, Zonneveld FW. Single-step fronto-orbital resection and reconstruction with individual resection template and corresponding titanium implant: a new method of computer aided surgery. J Craniomaxillofac Surg. 1998; 26: 373-378. DOI: 10.1016/S1010-5182(98)80070-X

31. Eufinger H, Wehmöller M. Microsurgical tissue transfer and individual computer-aided designed and manufactured prefabricated titanium implants for complex craniofacial reconstruction. Scand J Plast Reconstr Surg Hand Surg. 2002; 36: 326-331. DOI: 10.1080/02844302321096311

32. Ellis EE, Messo E. Use of nonresorbable alloplastic implants for internal orbital reconstruction. J Oral Maxillofac Surg; 2004; 62: 873-881. DOI: 10.1016/j.joms.2003.12.025

33. Bücheler M, Wehmöller M, Eufinger H, Bootz F. 2001; 49: 367-371. DOI: 10.1016/s0022-3999(00)00424-20

34. Machtens E, Eufinger H. Anwendung und Technik der computergestütz-vorgefertigten, individuellen Schädelimplantaten (CAD/CAM) - sechsjährige klinische Erfahrungen und Ausblick. Nova Acta Leopoldina. 2001; 84: 47-54.

35. Eufinger H, Rasche C, Lehmbrock J, Wehmöller M, Weidle S, Schmittz I, Schiller C, Epple M. Performance of functionally graded implants of polyactides and calcium phosphate / calcium carbonate in an ovine model for computer assisted cranioectomy and cranioplasty. Biomat. 2007; 28: 475-485. DOI: 10.1016/j.biomaterials.2006.08.055

36. Kamyaszek T, Weidle S, Scholz M, Wehmöller M, Eufinger H. Versorgung kraniofazialer Knochendefekte mit individuell vorgefertigten Titanimplantaten, Mund Kiefer Gesichtschir. 2001; 5: 233-238. DOI: 10.1017/s1000061000317

37. Altasalo KMI, Peitola MJ. Bioactive glass hydroxypatite fronto-orbital defect reconstruction. Plast Reconstr Surg. 2007; 120: 1963-1974. DOI: 10.1097/01.prs.0000287319.34254.27

38. Peitola M, Kinnunen I, Altasalo K. Reconstruction of orbital wall defects with bioactive glass plates. J Oral Maxillofac Surg. 2008; 66: 639-646. DOI: 10.1016/j.joms.2007.11.019

39. Ignatius A, Peraus M, Schorlemmer S, Augart P, Burger W, Leyen S, Claes L. Osseointegration of alumina with a bioactive coating under load-bearing and unloaded conditions. Biomat. 2005; 26: 2323-2332. DOI: 10.1016/j.biomaterials.2004.07.029

40. Siebert H, Schleier P, Beinemann J, Fried W, Zonneveld FW. Single-step prefabricated titanium implants in reconstructive craniofacial surgery: Clinical and technical aspects of the first 22 cases. Plast Reconstr Surg. 1998; 102: 300-308. DOI: 10.1097/00006534-19980800-00002

41. Dämmerich TD, Knapp FB, Bödeker CC, Klenzner T, Maier W, Schipper J. Kraniofaziale Fibröse Dysplasie: Observieren oder operieren? Laryngo-Rhino-Otol. 2007; 86: 184-192. DOI: 10.1055/s-2006-944766

42. Koscielný S, Belele E. Untersuchungen zum Einfluss von Bioerfern auf biologische Leistungen von Mikroorganismen. HNO. 2001; 49: 367-371.

43. Koscielný S, Belele E. Untersuchungen zum Einfluss von Bioerfern auf die Phagoyzrosatrate humaner Leukozyten. HNO. 2002; 50: 884-988.

44. Dall GF, Simpson PMS, Breusch SJ. In vitro comparison of Refobacin-Palacos R with Refobacin Bone Cement and Palacos R+G. Acta Orthop. 2007; 78: 404-411. DOI: 10.1080/17453670710013997

45. Gravius S, Wirtz DC, Marx R, Maus U, Andereya S, Müller-Rath R, Mumme T. Mechanische in-vitro-Prüfung von fünfzehn kommerziellen Knochenzementen auf der Basis von Polyethylmethacrylat. Z Orthop Unfall. 2007; 145: 579-585. DOI: 10.1055/s-2007-965666

46. Kock HJ, Huber FX, Hillmeier J, Jäger R, Volkmann R, Handschin R+G. Acta Orthop. 2007; 78: 404-411. DOI: 10.1055/s-2007-965666

47. Dost P, Eilermann S, Millföldt N, Jahnke K. Rekonstruktion des Stirnhöhlen mit individuellen Titanimplantaten. Mund Kiefer Gesichtschir. 2001; 5: 299-303. DOI: 10.1017/s1000061000317
60. Gosau M, Schiel S, Draenert GF, Ihrler S, Mast G, Ehrenfeld M. Gesichtsschädelaugmentationen mit porösen Methylenimplantaten (Medpor®). Mund Kiefer Gesichtschir. 2006; 10: 178-184. DOI: 10.1007/s10006-006-0688-y

61. Hohlweg-Majert B, Schön R, Schmelzeisen R, Gelrich NC, Schramm A. Navigational maxillofacial surgery using virtual models. World J Surg. 2005; 29: 1530-1538. DOI: 10.1007/s00268-005-0991-0

62. Betz MW, Caccamese JF, Coletti DP, Sault JJ, Fisher JP. Tissue response and orbital floor regeneration using cyclic acetal hydrogels. J Biomed Mater Res A. 2009;90(3):819-29. DOI: 10.1002/jbm.a.32131

63. Rinna C, Ungari C, Saltarel A, Cassoni A, Reale G. Orbital floor restoration. J Craniofac Surg. 2010; 16: 968-972. DOI: 10.1097/01.crs.0000386895.16795.8b

64. Taheri Telesh K, Babae S, Vahdati SA, Tabeshfar S. Effectiveness of a nasoseptal cartilaginous graft for repairing traumatic fractures of the inferior orbital wall. Brit J Oral Maxillofac Surg. 2009; 47: 10-13. DOI: 10.1016/j.bjoms.2008.04.017

65. Lin IC, Liao SL, Lin LLK. Porous polyethylene implants in orbital floor reconstruction. J Formos Med Assoc. 2007; 106: 51-57. DOI: 10.1016/S0929-6646(06)60216-3

66. Úzurk S, Sengör M, İsik S, Turegun M, Deveci M, Cil Y. Long-term outcomes of ultra-thin porous polyethylene implants used for reconstructive orbital floor defects. J Craniofac Surg. 2005; 16: 973-977. DOI: 10.1097/01.crs.0000179744.91165.3a

67. Nam SB, Bae YC, Moon SJ, Kang YS. Analysis of the postoperative outcome in 405 cases of orbital fracture using 2 synthetic orbital implants. Ann Plast Surg. 2006; 56:263-267. DOI: 10.1097/1.sap.0000199173.73610.bc

68. Yilmaz M, Vayvada H, Aydin E, Menderes A, Atabey A. Repair of traumatic fractures of the orbital floor with porous polyethylene implants. Ann Plast Surg. 2006; 56:263-267. DOI: 10.1007/s00268-006-0688-y

69. Röpke E, Bloching M. Mateialien in der rekonstruktiven Orbitachirurgie. Klin Monatsbl Augenheilkd. 2004; 221: 985-991. DOI: 10.1055/s-2004-813686

70. Schön R, Metzger MC, Zizelmann C, Weyer N, Schmelzeisen R. Individually preformed titanium mesh implants for a true-to-original repair of orbital fractures. Br J Oral Maxillofac Surg. 2006; 44: 640-644. DOI: 10.1016/j.bjoms.2007.06.004

71. Zizelmann C, Gelrich NC, Metzger MC, Schön R, Schmelzeisen R, Schramm A. Computer-assisted reconstruction of orbital floor based on cone beam tomography. Br J Oral Maxillofac Surg. 2007; 45: 79-80. DOI: 10.1016/j.bjoms.2006.05.031

72. Hoffmann J, Cornelius CP, Groten M, Pröbstler L, Schwenzer N. Verwendung individuell hergestellter Keramikimplantate zur Sekundärerekonstruktion der knöchernen Orbita. Mund Kiefer Gesichtschir. 1998; 2/Suppl 2: S98-S101.

73. Metzger MM, Schön R, Weyer N, Rafii A, Gelrich NC, Schmelzeisen R, Strong BE. Anatomical 3-dimensional pre-bent titanium implant for orbital floor fractures. Ophthalmology. 2006; 113: 1863-1868. DOI: 10.1016/j.opth.2006.03.062

74. Zizelmann C, Schramm A, Schön R, Ridder GJ, Maier W, Schipper J, Gelrich NC. Computerassisted Verfahren in der rekonstruktiven funktionserhaltenden Orbitachirurgie. HNO. 2005; 53: 428-438.

75. Büchel P, Rahal A, Seto I, Iizuka T. Reconstruction of orbital floor fracture with polyglactin 910 / polydioxanon patch (Ethisorb®): A retrospective study. J Oral Maxillofac Surg. 2005; 63: 646-650. DOI: 10.1016/j.joms.2004.11.013

76. Baumann A, Burggasser G, Gauss N, Ewers R. Orbital floor reconstruction with an alloplastic resorbable polydioxanone sheet. Int J Oral Maxillofac Surg. 2002; 31: 267-273. DOI: 10.1054/jjoms.2001.0091

77. Sinkovic B, Kramer FJ, Swennen G, Lübbers HT, Dempf R. Reconstruction of orbital wall defects with calcium phosphate cement: clinical and histological findings in a sheep model. Int J Oral Maxillofac Surg. 2007; 36: 54-61. DOI: 10.1016/j.joms.2006.07.014

78. Vagefi MR, McMullan TFW, Borroughs JR, White GL, McCann JD, Anderson RL. Injectable calcium hydroxyapatite for orbital volume augmentation. Arch Facial Plast Surg. 2007; 9: 439-442. DOI: 10.1001/archfaci.9.6.439

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