Bone Augmentation Procedures in Implant Dentistry

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Purpose: *This review evaluated (1) the success of different surgical techniques for the reconstruction of edentulous deficient alveolar ridges and (2) the survival/success rates of implants placed in the augmented areas.* ***Materials and Methods:*** *Clinical investigations published in English involving more than 10 consecutively treated patients and mean follow-up of at least 12 months after commencement of prosthetic loading were included. The following procedures were considered: onlay bone grafts, sinus floor elevation via a lateral approach, Le Fort I osteotomy with interpositional grafts, split ridge/ridge expansion techniques, and alveolar distraction osteogenesis. Full-text articles were identified using computerized and hand searches by key words. Success and related morbidity of augmentation procedures and survival/success rates of implants placed in the augmented sites were analyzed.* ***Results and Conclusion:*** *A wide range of surgical procedures were identified. However, it was difficult to demonstrate that one surgical procedure offered better outcomes than another. Moreover, it is not yet known if some surgical procedures, eg, reconstruction of atrophic edentulous mandibles with onlay autogenous bone grafts or maxillary sinus grafting procedures in case of limited/moderate sinus pneumatization, improve long-term implant survival. Every surgical procedure presents advantages and disadvantages. Priority should be given to those procedures which are simpler and less invasive, involve less risk of complications, and reach their goals within the shortest time frame. The main limit encountered in this literature review was the overall poor methodological quality of the published articles. Larger well-designed long-term trials are needed.* Int J Oral Maxillofac Implants 2009;24(suppl):237–259

Key words: *alveolar bone loss, alveolar ridge augmentation, atrophy, autogenous bone, graft material, oral implant*

Dental rehabilitation of partially or totally edentulous patients with oral implants has become a routine treatment modality in the last decades, with reliable long-term results.[1–12] However, unfavorable local conditions of the alveolar ridge, due to atrophy, periodontal disease, and trauma sequelae, may provide insufficient bone volume or unfavorable vertical, horizontal, and sagittal intermaxillary relationships, which may render implant placement impossible or incorrect from a functional and esthetic viewpoint.

Five main methods have been described to augment bone volume of deficient sites: *(1)* osteoinduction through the use of appropriate growth factors[13,14]; *(2)* osteoconduction, in which a grafting material serves as a scaffold for new bone formation[14,15]; *(3)* distraction osteogenesis, by which a fracture is surgically induced and the two bone fragments are then slowly pulled apart, with spontaneous bone regeneration between the two fragments[16,17]; *(4)* guided bone regeneration (GBR), which allows spaces maintained by barrier membranes to be filled with bone[18–25]; and *(5)* revascularized bone grafts, where a vital bone segment is transferred to its recipient bed with its vascular pedicle, thus permitting immediate survival of the bone and no need for a remodeling/substitution process.[26–29]

Whereas osteoinduction with growth factors such as bone morphogenetic proteins (BMPs) is still in an experimental phase and/or has extremely limited clinical applications, inlay or onlay bone grafts, GBR, split ridge/ridge expansion techniques, and alveolar distraction osteogenesis represent commonly applied

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methods to recreate correct intermaxillary relationships and adequate bone morphology and volume for implant placement. Yet, despite an increasing number of publications related to the correction of deficient edentulous ridges, much controversy still exists concerning which is the more suitable and reliable technique. This is often because the publications are of insufficient methodological quality (inadequate sample size, lack of well-defined exclusion and inclusion criteria, insufficient follow-up, lack of well-defined success criteria, etc).

The objective of this review was to analyze publications related to augmentation procedures and to evaluate *(1)* the success of different surgical techniques for the reconstruction of the deficient alveolar bone and *(2)* the survival/success rates of implants placed in the reconstructed areas.

CRITERIA FOR CONSIDERING STUDIES

Types of Studies

The basis of this review was represented by the reviews published by Hämmerle et al,[25] Esposito et al,[30] and Chiapasco et al.[31] To expand these reviews and not limit the literature search to randomized clinical trials, any clinical investigation published in the English language and involving more than 10 consecutively treated patients, with a mean follow-up of at least 12 months after the start of prosthetic loading, was included.

It is worth noting that the authors arbitrarily decided to use a minimum *mean* follow-up of 12 months (not a minimum follow-up of 12 months) as a cutoff, because many publications reported wide ranges of follow-ups. To remove these articles could have meant a loss of valuable data.

Publications in which the same data were reported in later publications by the same groups of authors were not considered.

Types of Participants

Only patients presenting with deficient edentulous ridges following atrophy, periodontal disease, and trauma sequelae were considered. Patients affected by bone defects following ablation for tumors or osteoradionecrosis, as well as bone defects related to congenital malformations (such as cleft lip and palate or major craniofacial malformations), were excluded from this analysis because the initial clinical situation is very different and not comparable.

Types of Interventions

Only articles related to endosseous root-form titanium implants were considered. The following surgical procedures were considered: onlay bone grafts, sinus floor elevation via a lateral approach, Le Fort I osteotomy with interpositional grafts, split-ridge/ridge expansion techniques, and alveolar distraction osteogenesis. Guided bone regeneration procedures and correction of dehiscences and fenestrations were excluded from this review because they are described and discussed by Jensen and Terheyden in a parallel review in this same issue. Also, pre-implant reconstructions with revascularized free flaps were excluded from this review, as no articles fulfilling our inclusion criteria were found in the literature.

Outcome Measures

Success rates of augmentation procedures, related morbidity, as well as survival and success rates of implants placed in the augmented sites were analyzed.

SEARCH METHOD

Full-text articles published in English were found with a computerized search through MEDLINE from 1975 to January 2008. Key words used in the search included: *atrophy, alveolar bone loss, mandible, maxilla, edentulous jaw, edentulous maxilla, edentulous mandible, preprosthetic surgery, oral surgical procedure, alveolar ridge augmentation, oral implant, osseointegrated implant, dental, endosteal, endosseous, dental implantation, implant-supported, dental prosthesis, implant-supported dental prosthesis, guided bone regeneration, guided tissue regeneration, bone transplantation, graft, bone graft, onlay bone graft, calvarium, iliac crest, ilium, distraction osteogenesis, expansion, Le Fort I, maxillary sinus, sinus lift, sinus floor elevation, oral sagittal osteotomy, split crest, ridge expansion, humans, follow-up study, retrospective study, prospective study, comparative study, randomized clinical trials, free flap, revascularized free flap, fibula, iliac free flap, morbidity, donor, distraction osteogenesis, alveolar distraction osteogenesis, inlay bone graft, allograft, xenografts,* and *alloplastic*.

To expand this, a hand search of journal issues from 1975 through January 2008 was undertaken on the following journals: *Clinical Oral Implants Research; The International Journal of Oral & Maxillofacial Implants; Journal of Oral and Maxillofacial Surgery; International Journal of Oral and Maxillofacial Surgery; Journal of Cranio-Maxillo-Facial Surgery; Journal of Prosthetic Dentistry; Scandinavian Journal of Plastic and Reconstructive Surgery; Dental Clinics of North America; Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology; Clinical Implant Dentistry and Related Research; British Journal of Oral and Maxillofacial Surgery; International Journal of Periodontics*

& Restorative Dentistry; Journal of Periodontology; European Journal of Prosthodontics and Restorative Dentistry; Plastic and Reconstructive Surgery; and *Journal of Oral Surgery*. Other articles were identified from the reference lists of the articles found.

Selection Criteria and Data Extraction

The titles and abstracts (when available) of all reports identified were analyzed by the authors. For studies appearing to meet the inclusion criteria, or for which there was sufficient data in the title and the abstract to make a clear decision, the full text of the article was obtained. Data retrieved were recorded on flow sheets including: year of publication; type of study; details of participants, including criteria of inclusion/exclusion; details of the type of intervention; and details of the outcomes reported.

Two independent researchers performed the search of available publications.

RESULTS

The results of the literature review (patients and methods, outcomes, and discussion) are presented separately for each of the five types of surgical interventions.

Onlay Bone Grafts

Patients and Methods. The search provided 331 studies, of which 126 were screened as full text. Of these publications, only 26 were included[12,32–56] (Table 1). Of the 26 publications included in this review, 21 were retrospective studies and 5 were prospective studies; no randomized clinical trials were found.

Overall, 893 patients, presenting with alveolar defects of the jaws that did not allow the placement of implants of adequate dimensions and/or in a correct position from a functional and esthetic viewpoint, were treated by means of autogenous bone grafts taken from intraoral or extraoral sites; 593 defects were localized in the maxilla and 179 in the mandible. Due to insufficient data, it was not possible to attribute the location of atrophy for 149 defects. The number of defects and grafts does not correspond to the number of patients because in some cases bilateral defects as well as defects involving both the mandible and the maxilla were present in the same patient.

Autogenous bone was harvested from the iliac crest in 687 patients, from the calvarium in 44 patients, and from intraoral sites (mental symphysis, mandibular body/ramus, and maxillary tuberosity) in 183 patients. The harvested bone was used as a block in the majority of cases. Particulated bone was associated with bone blocks in cases of simultaneous sinus grafting procedures or as a filling material around/between bone blocks. The bone was used alone in 862 patients, or mixed with allografts or alloplastic materials (hydroxyapatite [HA], β-tricalcium phosphate [TCP]) in 31 patients.

Of 897 defects, 593 involved extended edentulous areas (subtotal or total edentulism of one or both jaws), while 304 had limited extension (one to four missing teeth, on average). A total of 4,390 implants were placed; of these, 291 were placed in reconstructed mandibles and 2,463 in reconstructed maxillae, while for 1,636 implants it was not possible to determine the site of placement (publications reporting both mandibular and maxillary reconstructions). Of the 4,390 implants, 2,186 were placed at the same time as the reconstruction and 1,561 were inserted 3 to 8 months after the reconstructive procedure. For the remaining 643 implants it was not possible to determine the timing of insertion. Of 4,390 implants placed, 3,351 were machined-surface titanium implants and 288 were rough-surfaced implants (including different types of surfaces such as plasma-spray, acid-etched, sandblasted, and HA-coated), while for the remaining 751 implants it was not possible to retrieve pertinent data on the implant surface, either because the implant surface was not specified or because both machined-surface and rough-surfaced implants were used in the same study.

Patients were rehabilitated with both fixed and removable implant-supported prostheses. Prosthetic rehabilitation was started 2 to 26 months after implant placement, with the majority of articles reporting a 4- to 6-month waiting period. Early loading (2 months after implant placement) of implants placed in the reconstructed areas was reported in one publication.[50] Follow-up of patients after the start of prosthetic loading of implants ranged from 6 to 240 months (Table 1).

Outcomes. Postoperative morbidity related to bone harvesting from intraoral sites is mainly represented by temporary neural disturbances involving branches of the inferior alveolar nerve. As reported in the literature, the incidence of neural disturbances related to bone harvesting from the chin ranges from 10% to 50%, whereas those related to bone harvesting from the mandibular ramus range from 0% to 5%.[45,57–60] However, only one of the articles selected for this review reported data related to this aspect[45]: both ramus and chin were used for bone harvesting, and temporary neural disturbances occurred in 0% and up to 80% of the cases, respectively, whereas permanent paresthesia to anterior mandibular teeth occurred in 0% and 13% of the patients, respectively.

For this reason, chin grafts should be considered with more caution, whereas the mandibular ramus is

Table 1 Onlay Bone Grafts (Maxilla and Mandible)—Characteristics of Included Studies

Study	Study type	No. of patients	Defect type (type of atrophy)	Donor site	Graft success (%)	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival (%)	Implant success (%)
Adell et al (1990)[32]	RS	23	Maxilla (hor-vert)	Ilium	ND	124 (imm)	Machined	12–120	73.8	ND
Jensen and Sindet-Pedersen (1991)[33]	RS	15	Maxilla (hor-vert)	Ilium/chin	ND	74 (imm)	Machined	6–26	90.2–92.3	ND
Donovan et al (1994)[34]	RS	24	Max+Mand (hor-vert)	Calvarium	100	43 (imm) 50 (del)	Machined	6–45	86–98	ND
McGrath et al (1996)[35]	RS	18	Mandible (hor-vert)	Ilium	100	36 (imm)	HA-coated	12–32	91.6	91.6
Åstrand et al (1996)[36]	RS	17	Maxilla (hor-vert)	Ilium	100	92 (imm)	Machined	36–60	75	ND
Vermeeren et al (1996)[37]	RS	31	Mandible (hor-vert)	Ilium	100	78 (imm)	Rough	12–60	90	ND
Triplett and Schow (1996)[38]	RS	99	Max+Mand (hor-vert)	Ilium/Calvarium/ Chin	90–100	65 (imm) 154 (del)	Machined	12	ND	90.7
Schliephake et al (1997)[39]	RS	137	Max+Mand (hor-vert)	Ilium/Chin	ND	550 (imm) 321 (del)	Machined	12–120	83.4 (1 y) 67.8 (5 y)	ND
van Steenberghe et al (1997)[40]	RS	13	Maxilla (hor-vert)	Ilium	92	72 (imm)	Machined	12–120	ND	85
Verhoeven et al (1997)[41]	PS	13	Mandible (hor-vert)	Ilium	92	30 (imm)	Rough	6–36	100	ND
Lundgren et al (1997)[42]	RS	10	Maxilla (hor-vert)	Ilium	ND	70 (del)	Machined	12–32	80	ND
Widmark et al (1998)[43]	PS	16	Maxilla (hor-vert)	Ilium	ND	81 (imm) 20 (del)	Machined	12	83	83
Keller et al (1999)[44]	RS	32	Maxilla (hor-vert)	Ilium/Calvarium	96	183 (imm) 21 (del)	Machined	7–144	86.3	ND
Chiapasco et al (1999)[45]	CCT	15	Max+Mand (hor)	Ilium/Calvarium/ Chin	100	44 (del)	Rough/ Machined	18–36	100	90.9
Lekholm et al (1999)[46]	RS	56	Maxilla (hor-vert)	Intraoral/Ilium	ND	181 (imm) 75 (del)	Machined	36	60–84	ND
Bahat and Fontanessi (2001)[47]	RS	62	Max+Mand	Ilium/Ramus allograft	92	21 (imm) 310 (del)	ND	12–96	93	93
Bell et al (2002)[48]	RS	14	Mandible	Ilium	100	70 (del)	Rough/ machined	24–48	100	ND
Becktor et al (2002)[49]	RS	90	Maxilla (hor-vert)	Ilium	ND	643 (imm/del)	Machined	22–105	71.6	ND
Raghoebar et al (2003)[50]	PS	10	Maxilla (hor-vert)	Ilium	100	68 (del)	Rough	12	95.6	95.6
Jemt and Lekholm (2003)[51]	PS	10	Maxilla	Chin	100	10 (del)	Machined	24	100	100
Becktor et al (2004)[12]	RS	64	Maxilla (hor-vert)	Ilium	ND	260 (imm) 177 (del)	Machined	27–100	75.1	ND
Iizuka et al (2004)[52]	RS	13	Max+Mand (hor-vert)	Calvarium	100	42 (del)	Rough	6–42	100	97.6
Nyström et al (2004)[53]	RS	30	Maxilla (hor-vert)	Ilium	ND	177 (imm)	ND	36–60	72.8–82.5	ND
van der Meij et al (2005)[54]	RS	13	Mandible	Ilium+HA	92	34 (imm)	Rough	6-90	88.2	88.2
Molly et al (2006)[55]	RS	18	Maxilla	Ilium	ND	85 (imm)	Machined	36–240	77.2–86.7	ND
Levin et al (2007)[56]	RS	50	Max+Mand	Intraoral	ND	129 (del)	ND	6–67	96.9	91.9

RS = retrospective study; PS = prospective study; CCT = controlled clinical trial; max = maxilla; mand = mandible; hor = horizontal defect; vert = vertical defect; TCP = tricalcium phosphate; FDBA = freeze-dried bone allograft; HA = hydroxyapatite; graft success = success rate of the grafting procedure; imm = immediate placement; del = delayed placement; ND= no data.

gaining in popularity due to its advantages as compared to the mental symphysis: the quality of bone is similar (relevant cortical component), the quantity may be greater, and the risk of neural damage is lower.

In cases of bone harvesting from the iliac crest, temporary pain/gait disturbances were the most frequent complaints, but only 9 out of 22 articles reported data on this topic. Long-standing pain/gait disturbances were reported only in 2% of the cases.[33,37,40,42,45,48,61]

In cases of bone harvesting from the calvarium, morbidity was extremely low (0% in the reviewed articles), but only 3 out of 5 articles dealing with calvarial grafts reported pertinent data.[34,45,52]

Uneventful healing/consolidation of both intraoral and extraoral grafts occurred in the majority of patients. Partial loss of the graft due to wound dehiscence/infection occurred in 3.3% of the cases, while total loss of the graft occurred in 1.4% of the cases,[38,40] the majority being related to extensive reconstructions of atrophic maxillae with iliac grafts. However, it is worth noting that only 16 out of 26 articles reported data on this topic. Overall, the survival rate of implants placed in reconstructed maxillae and mandibles was 87% (range 60% to 100%; median 91.5%).

To obtain more information, the survival rates of implants were analyzed according to site of atrophy (maxilla or mandible), type of implant surface, timing of implant placement (in conjunction with the reconstructive procedure or after the consolidation of the graft), and type of graft (intraoral, calvarial, iliac). However, this analysis was limited by the fact that publications did not always separate data concerning these issues.

The overall survival rate of implants placed in reconstructed maxillae (both with one-stage and two-stage placement) after follow-up periods ranging from 6 to 240 months was 79.5% (range 60% to 100%; median 82.7%; mean 81.6% (496 implants were removed out of 2,413 placed).

The mean survival rate of implants placed in conjunction with maxillary reconstructions was 81.8% (range 72.8% to 92.3%). However, it was possible to retrieve pertinent data only from 5 out of 16 articles.[33,36,40,53,55]

The mean survival rate of implants placed in reconstructed maxillae with a staged approach was 89.9% (range 80% to 100%). However, it was possible to retrieve pertinent data only from 3 out of 15 articles.[42,50,51]

Although a higher failure rate was found in patients receiving implants in conjunction with bone grafts, it is difficult to report significant data because 16 out of 21 articles dealing with maxillary reconstructions did not separate maxillary from mandibular implants and/or immediate and delayed implant placement.

The overall survival rate of implants placed in reconstructed mandibles (both with one-stage and two-stage placement) was 94.8% (range 88.2% to 100%; median 91.5%; mean 94%) for a follow-up period of 6 to 90 months (see Table 1 for details).

Implant survival rate was 91.1% (range 88.2% to 100%) for implants placed in conjunction with mandibular reconstruction and 100% for those placed in a staged approach. All implant losses occurred in patients receiving implants at the same time as reconstruction (see Table 1 for details).

With regard to the survival rate of implants according to type of implant surface, it was observed that machined-surface implants showed on average a lower survival rate (range 60% to 100%; median 83%; mean 81.6%) than rough-surfaced implants (range 90% to 100%; median 93.5%; mean 94.2%). However, it must be emphasized that sample sizes were very different (3,351 machined-surface implants and 288 rough-surfaced implants), and no statistically significant comparisons can be made (see Table 1).

As far as the relationship between survival rate and donor site is concerned, the retrieved data demonstrated that the majority of implant failures occurred in patients reconstructed with iliac grafts (failure rate 17.5%). The failure rate for implants placed in calvarial grafts was 6% and that for implants placed in intraoral grafts was 5.5% (see Table 1). However, these percentages should be evaluated with caution because some publications in which different donor sites were used did not separate implant failures according to donor site distribution.

Data were even more insufficient in terms of success rates of implants according to well-defined criteria: only 13 of 26 publications specified the criteria for implant success evaluation (see Table 1). The success rate ranged from 83% to 100% (median 89%), with the majority of articles reporting success rates > 90%, but it is worth noting that the number of implants reported in the above-mentioned publications represented only one-fourth of the total number of implants placed in the grafted jaws (see Table 1).

Discussion. The analysis of available publications demonstrated, on average, poor methodological quality with regard to resorption pattern of the grafted bone, timing of implant placement, evaluation of success of implants according to well-defined criteria, success rate of implants according to type of graft and implant location, and duration of follow-up. A far as this latter aspect is concerned, we had to make some compromises in including articles, because some of them had an extremely wide range of follow-up periods. Some articles with follow-up of

more than 10 years also included patients with a follow-up of 6 months. As one of our initial requirements was a minimum follow-up of 1 year for the inclusion of patients, we had to modify this to require a minimum *mean* follow-up of 1 year to avoid the loss of a relevant amount of data.

Moreover, of 26 publications included in this review, 21 were retrospective clinical series and 5 were prospective studies; no randomized clinical trials were found. However, within the limits determined by the lack of data from randomized clinical trials, some conclusions can be drawn on the following topics.

Bone Resorption Pattern of the Grafted Bone. In the past, before the advent of osseointegrated implants, the reconstruction of atrophic edentulous ridges with onlay bone grafts was criticized because of the relevant resorption that followed prosthetic loading.[62] However, these results were mainly due to the use of completely removable dentures, which adversely affected not only the grafted jaws, but also the non-grafted edentulous ridges.[63] The use of onlay grafts has been reevaluated since the advent of osseointegrated screw-type implants, which seem to inhibit resorption of the residual as well as of the transplanted bone, as demonstrated by a number of publications.[12,34,39,40,42,45,46,49,51,53] However, the capacity of bone grafts in maintaining the original bone volume is variable, and results reported in the literature are contradictory, due to relevant differences in observation periods, type and site of reconstruction, timing of implant loading, use or non-use of provisional dentures on reconstructed sites, and, last but not least, the site of bone harvesting. Overall, there is a paucity of information as far as bone resorption of grafts is concerned. This is because many papers report only survival rates of implants placed in grafts, with no measurement of modifications of graft dimensions, in particular concerning horizontal bone resorption.

With regard to vertical bone resorption of onlay grafts, the following conclusions can be drawn, despite the limits caused by the paucity of available data:

- Bone resorption is greater in the first year after the reconstruction and in the first year after loading of implants, with a significant reduction in the following years.[64]
- Relevant differences in bone resorption were found according to donor sites. In the case of iliac grafts, resorption rates of the initial graft height 1 to 5 years postloading of implants ranged from 12% to 60%.[36,37,39,41–43,46,53,54] In the case of intraoral grafts, there are insufficient data to draw any meaningful conclusion. The best results were found for vertical reconstruction with calvarial grafts, where resorption rates ranged from 0% to 15% of the initial graft height.[34,52] This seems to indicate that cortical thickness and density of donor bone are factors which might influence the resorption pattern.
- Oversized grafts should be harvested to maintain enough graft volume after the initial resorption phase.
- If autogenous bone grafts are used, it is highly recommended to use corticocancellous bone blocks. Cancellous bone alone and particulated bone, if not associated with membranes of titanium meshes, do not provide sufficient rigidity to withstand tension from the overlying soft tissues or from the compression by provisional removable dentures, and may undergo almost complete resorption.[65,66]

Even fewer data are available regarding resorption of horizontal bone grafts, due to the greater difficulty in measuring this parameter (need for computed tomography or calipers instead of simpler methods such as intraoral radiographs). Only two articles reported data on horizontal bone resorption of the graft, which ranged from 10% to 50%.[45,51]

This review seems to demonstrate that, despite the limits mentioned above, reconstruction of atrophic edentulous or partially edentulous jaws with autogenous bone grafts is an acceptable modality in restoring dentition with implant-supported prostheses. However, the pros and cons of bone transplantation must be carefully weighed in terms of economic and biologic costs (morbidity). In particular, the size and the site (maxilla or mandible) of the defect must be carefully evaluated.

In cases of moderate/severe atrophy in partially edentulous patients, other surgical options, such as distraction osteogenesis, guided bone regeneration, and sagittal osteotomies, which may present less morbidity, should be considered. Moreover, it is necessary to consider the area where atrophy has occurred. In recent years, an increasing number of articles related to the use of short implants with apparently acceptable survival rates after the start of prosthetic loading have been published.[67–74] In particular, the atrophic posterior areas, where esthetic problems are frequently not as relevant (with the exception of patients with a gummy smile), may be treated with short implants without any previous reconstruction, taking into account, however, that longer superstructures may represent a prosthetic and functional compromise. On the contrary, the atrophic maxilla does not appear to be "the right candidate" for the use of short implants, as long teeth may represent an unacceptable solution for the

majority of patients. Therefore, patients' expectations should be carefully evaluated preoperatively before a decision is made.

In severely atrophied edentulous maxillae, relevant resorption of the alveolar process and the presence of nasal and paranasal cavities (maxillary sinuses) leads to a clinical situation that is not compatible with implant placement, because of insufficient quantity and low quality of the residual bone. In these cases, onlay grafts (with or without associated sinus grafts—see next sections for more details) are one of the few options that permit the re-creation of a more favorable environment for implant placement. Other surgical options, such as Le Fort I osteotomy with interpositional bone grafts and microvascular free flaps, are accompanied by even more morbidity, and should be limited to extreme atrophy or severe intermaxillary discrepancy not amenable to treatment with onlay grafts (see next sections for further details).

Conversely, the edentulous mandible, although severely atrophied, may present local conditions that are compatible with safe implant placement also without complex, technically and biologically demanding procedures. It has been demonstrated that, also in the case of severe atrophy, the dense, highly corticalized bone of the mandibular symphysis is able to support the functional demands of removable or fixed implant-supported prostheses also when short implants (less than 10 mm) are used.[75,76] According to the protocol proposed by Keller,[75] short implants can be placed in severely atrophic mandibles without reconstruction when the anterior mandible (interforaminal area) is more than 5 mm in height and at least 6 mm in width. Fifty-seven patients presenting with such conditions received 260 implants loaded with removable or fixed implant-supported prostheses. The survival rate of implants was 93.1%, after a mean follow-up of 59 months, with no significant differences compared to the survival rate of implants placed in atrophic nonreconstructed mandibles. Therefore, reconstruction of the atrophic mandible should be limited to cases where the mandibular bone height and width are less than 5 mm and 6 mm, respectively. In this situation the residual available bone is insufficient for harboring implants of adequate dimensions, and there is a risk of "fatigue" fractures of the mandible. However, if reconstruction of the mandible is the chosen option, calvarial grafts should be preferred to iliac grafts, due to the very limited resorption.[34,52,77] It has been shown that iliac onlay grafts for the reconstruction of edentulous mandibles are exposed to relevant resorption (up to 50%),[37,41] and therefore their use is now questionable.

Timing of Implant Placement. Implant placement both in conjunction with bone grafting and after consolidation of bone grafts have been proposed. Those who advocate simultaneous implant placement[33,36,37,40,41,44,46,53–55,61,78] base their opinion on the fact that resorption of an onlay graft over time is not a linear process but is most pronounced soon after its transplantation.[41,64] Simultaneous implant placement will shorten the waiting time before rehabilitation, thus potentially reducing the risk of bone resorption.

Those who advocate delayed placement[38,42,45,47,48,50–52,56,77] think that simultaneous placement of implants may expose the patient to some risks, which can be summarized as follows: In the case of wound dehiscence, exposure and infection/necrosis of the bone graft may occur and lead to partial or total loss of the graft; immediate implants are placed into avascular bone, which increases the risk of nonintegration.

Conversely, when a delayed protocol is performed, it will be possible to place implants in a revascularized (albeit partly) graft. Since the regenerative capacity of bone is determined by the presence of vessels, bone marrow, and vital bone surfaces, a delayed approach will permit better integration of implants (higher values of bone-implant contact) and better stability of implants, as compared to immediate implant placement.[42,79–81]

Despite these considerations, however, much controversy still exists in terms of timing of implant placement in grafted areas, and no conclusions can be drawn.

Loading Time of Implants Placed in Grafted Areas. Initial reports recommended longer waiting times (6 to 12 months) between implant placement and subsequent abutment connection and prosthetic loading. The rationale was to allow some extra time for graft incorporation, but not too long, taking advantage of the theoretical ability of implants to provide a bone-preserving stimulus in the same way that the presence of healthy teeth preserves the alveolar bone.[61] However, although no conclusive recommendations can be made due to the wide range of waiting times proposed and to the different characteristics of macro-, micro-, and nanogeometry of different implant systems (which may influence osseointegration times), the majority of authors cited in this review suggested waiting times similar to those proposed for implants placed in nonreconstructed bone (3 to 6 months), with no detrimental effects on osseointegration.

It has also been demonstrated by means of resonance frequency measurements that implants placed in grafted bone can achieve stability similar to that of implants placed in native bone only 24 weeks after

their placement.[82] Therefore, longer waiting periods appear to be questionable.

Although limited, there is also evidence that early or immediate loading of implants placed in reconstructed areas may lead to successful integration. Raghoebar et al[50] reported data on early loading (2 months after implant placement) of implants placed in edentulous maxillae augmented with onlay iliac grafts. Of 68 implants placed in 10 patients, 65 survived (95.6%) after 1 year of functional loading. Chiapasco et al[77] reported data on immediate loading (within 48 hours after implant placement) of implants placed in reconstructed edentulous mandibles with calvarial onlay grafts. Of 23 implants placed in six patients, 23 survived (100%) after a follow-up of 12 to 36 months postloading.

Survival and Success Rates of Implants. Survival and success rates of implants placed in reconstructed jaws are, on average, lower than those of implants placed in native bone, in particular in cases where extensive reconstructions were performed. However, it is worth noting that only a few publications reported data based on well-defined criteria. In particular, only two studies[39,49] applied thorough statistical methods for the evaluation of clinical outcomes, with the objective to correlate implant survival/success with factors such as type and dimension of implants, type of opposing arch dentition, type of augmentation technique, patients' gender, and site of reconstruction. The conclusions were as follows:

- The cumulative survival rate of implants demonstrated a progressive decline from 1 to 5 years following the start of prosthetic loading.
- Implants placed in edentulous reconstructed maxillae were associated with survival rates lower than implants placed in reconstructed mandibles. Conversely, the difference between partially edentulous maxillae and mandibles was not statistically significant.
- Onlay grafts from the iliac crest were associated with survival rates lower than grafts harvested from the mandible.
- The time at which implants were inserted into the bone grafts showed no significant effect on the survival rate.
- Implant survival rate tended to improve with increasing implant length.
- The patients' age had no significant impact on implant survival.
- A higher failure rate was found in female patients.
- Many implant failures in the maxilla occurred in only a few patients.
- Implants opposing unilateral occlusal support showed the highest rate of implant failure.
- Implants that opposed a mandibular implant-supported fixed prosthesis or a removable mandibular denture presented the lowest failure rate.

Sinus Floor Elevation

Patients and Methods. The search provided 1,039 studies related to sinus floor elevation via a lateral approach, of which 501 were screened as full-text articles. Of these publications, only 59 were included in the review.[38,44,46,83–138] Some studies, although fulfilling the inclusion criteria, were not considered because the same data were reported in later publications by the same group of authors. Also, as previously stated, transalveolar sinus floor elevation was not considered, as it is analyzed in a parallel review by Jensen and Terheyden in this supplement. Two of the selected studies reported data related to both transalveolar and lateral approaches[95,130]; only the cases related to the lateral approach were considered for this review.

Of the 59 selected studies, 41 were retrospective studies, 12 were prospective studies, 4 were controlled clinical trials, and only 2 were randomized clinical trials. Overall, 4,630 patients were treated by means of 5,573 maxillary sinus augmentation procedures. However, some articles reported only the number of patients without specifying the number of sinus grafting procedures.[46,88,95,107,132,136] A total of 13,889 implants were placed; of these, 5,632 were placed at the same time as the augmentation procedure and 5,271 at a second stage, while for 2,986 implants the timing of implant placement was not specified. Of 13,889 implants placed, 2,431 were machined-surface titanium implants, 6,249 were rough-surfaced implants (including various implant surfaces such as plasma-sprayed, sandblasted, acid-etched, and HA-coated), while for the remaining 5,209 implants it was not possible to retrieve pertinent data on implant surface, either because the implant surface was not specified or because both machined and rough-surfaced implants were used in the same publication.

In 23 out of 59 studies, one grafting material (autogenous bone, bovine bone mineral, calcium sulfate, hydroxyapatite, or allograft) was used alone. In the remaining studies, mixtures of different grafting materials were used, such as autogenous bone + bovine bone mineral (BBM), autogenous bone + HA or TCP, autogenous bone + allograft, HA + allograft, BBM + allograft, autogenous bone + platelet-rich plasma (PRP), allograft + PRP, and BBM + PRP. Only one article reported data on sinus floor elevation without the use of grafting materials[136]; in that study, the mucosa was maintained elevated by implants placed in conjunction with sinus surgery.

Patients were rehabilitated with both fixed and removable implant-supported prostheses. Prosthetic rehabilitation was started 2 to 52 weeks after implant placement (on average 24 weeks after). The follow-up period after the start of prosthetic loading ranged from 6 to 144 months (Table 2).

Outcomes. Data related to intraoperative and postoperative complications were reported in 40 of 59 articles. Uneventful healing of the augmentation procedure occurred in the great majority of the patients. The most frequent intraoperative complication was sinus membrane perforation, which occurred in approximately 10% of the cases (range 4.8% to 58%). In the vast majority of patients, sinus grafting was completed either by closing the perforation with resorbable materials, such as collagen sponge, resorbable membranes, or allograft sheets, or simply by increasing sinus floor mucosa elevation, with no further complications. Only in a very limited number of patients (less than 1%) did the grafting procedure have to be stopped, due to large tears in the membrane.

Postoperative complications occurred in approximately 3% of the patients. The most frequent was infection and/or postoperative maxillary sinusitis. Partial or total graft loss occurred in less than 1% of the patients, whereas the incidence of sinusitis ranged from 0% to 27% (average 2.5%). However, these data were reported in only 40 out of 58 articles, and therefore they must be interpreted with caution.

Overall, 778 out of 13,889 implants were removed. Survival rates of implants ranged from 60% to 100% in the selected studies (median 95%), with the majority of articles reporting values higher than 90%. Success rates of implants according to well-defined criteria ranged from 74.7% to 100% (median 98.5%) (Table 2). However, only 22 out of 59 articles reported data according to well-defined criteria. Therefore, these data should be interpreted with caution.

To obtain more information, the survival rates of implants according to type of graft (autografts, allografts, xenografts, alloplastic materials, or mixtures of those materials), timing of implant placement (in conjunction with the reconstructive procedure or after the consolidation of the graft), type of implant surface, and the quantity and quality of residual bone before grafting procedures should be analyzed. However, meaningful comparisons were rarely possible because the number of patients treated with different materials differed greatly; many publications in which different combinations of grafting materials were used reported data without separating them according to grafting material; and the quantity and quality of residual bone in the posterior maxilla were not always reported, although these parameters may greatly influence the final outcome of implants.

Survival Rates of Implants According to Grafting Material. The use of different filling materials apparently did not significantly influence survival rates of implants (see Table 2). However, comparisons are difficult, due to relevant differences in patients' samples, number of implants placed, and the type of implant surface. Moreover, it was frequently difficult or impossible to retrieve pertinent data related to survival of implants because in many articles different materials or different mixtures were used without separating results.

Only four studies prospectively compared the clinical outcome of implants according to different grafting materials: *(1)* Fugazzotto and Vlassis[96] (Bio-Oss versus allografts and TCP); *(2)* Hallman et al[114] (autogenous bone versus Bio-Oss and a mixture of autogenous and BBM); *(3)* Velich et al[128] (autogenous bone versus calcium carbonate, autogenous bone + HA, autogenous bone + TCP, HA alone, TCP alone, TCP + PRP); and *(4)* Valentini and Abensur[118] (allograft + BBM versus BBM alone). No relevant differences were found, but again, comparison of survival rates is difficult because both immediate and delayed implant placement were performed, thus introducing a bias that may influence the results.

Survival Rate of Implants According to Timing of Implant Placement. As far as the timing of implant placement is concerned, the survival rate of implants placed in conjunction with the grafting procedure ranged from 61.2% to 100% (mean 95%; median 100%), and from 72.7% to 100% (mean 93.7%; median 94%) in the case of a staged approach. However, many articles reporting on both immediate and delayed implant placement did not separate implant failures according to timing of implant placement. It was therefore difficult to obtain reliable information concerning this topic. A staged approach was generally suggested when the residual bone height might be insufficient to guarantee primary stability of implants (on average, when the residual bone height of the alveolar crest was less than 4 mm), while an immediate approach was suggested when enough bone volume was present to allow adequate primary stability of implants (> 5 mm). Only one article[93] reported a successful outcome of implants placed in conjunction with the grafting procedure with a very limited residual bone height (1 to 2 mm). Therefore, no clear indications concerning the timing of implant placement were found in the literature.

A single randomized trial[108] compared 20 patients treated with sinus grafting by means of iliac bone blocks and immediate implant placement with 20 patients treated with particulated iliac bone and

Table 2 Sinus Lifting Procedure (Lateral Approach)—Characteristics of Included Studies

Study	Study type	No. of patients	No. of SFE	Grafting material	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival (%)	Implant success (%)
Kent and Block (1989)[83]	RS	11	18	AB	54 (imm)	HA-coated	12–48	100	ND
Tidwell et al (1992)[84]	RS	48	83	AB+HA	203 (del)	HA-coated	12–32	93.6	ND
Raghoebar et al (1993)[85]	RS	25	47	AB	93 (ns)	machined	6–36	94.6	ND
Block and Kent (1993)[86]	RS	32	51	AB/AB+AG/AG	173 (ns)	ND	24–120	75	ND
Chiapasco and Ronchi (1994)[87]	RS	30	43	AB+BBM	41 (imm) 83 (del)	Rough	12–24	93.5	93.5
Hürzeler et al (1996)[88]	RS	133	ND	Various	235 (imm) 105 (del)	Rough	12–60	98.8	90.3
Triplett and Schow (1996)[38]	RS	70	70	AB	69 (imm) 76 (del)	machined	>12	82.6–90.8	ND
Wheeler et al (1996)[89]	RS	24	36	HA/BBM/AB/ AB+HA	66 (ns)	Rough/ machined	6–66	92.4	92.4
Raghoebar et al (1997)[90]	RS	43	81	AB	171 (ns)	Machined	8–62	94.7	ND
Block and Kent (1997)[91]	RS	33	53	AB/AG	173 (ns)	ND	36–134	88.4	ND
Watzek et al (1998)[92]	RS	20	40	BBM/AB+BBM/ AB+HA/AB	145 (del)	Rough	12–70	95.2	74.7
Peleg et al (1998)[93]	PS	20	20	AG+AB	55 (imm)	HA-coated	15–39	100	100
van den Bergh et al (1998)[94]	RS	42	62	AB	161 (del)	Rough	12–72	100	ND
Zitzmann and Schärer (1998)[95]	RS	10	ND	BBM	7 (imm) 13 (del)	Machined	6–24	100	ND
Fugazzotto and Vlassis (1998)[96]	RS	181	194	BBM/AG/TCP	181 (imm) 252 (del)	Rough	6–73	97	97
Blomqvist et al (1998)[97]	PS	50	97	AB	202 (del)	Machined	9–48	84.2	ND
Block et al (1998)[98]	RS	16	27	AB/AB+AG	73 (imm)	HA-coated	63–126	95.9	ND
Peleg et al (1999)[99]	PS	21	24	AG+AB	57 (imm)	HA-coated	36	100	ND
Mazor et al (1999)[100]	PS	10	10	AG+AB	10 (imm)	HA-coated	36	100	100
Peleg et al (1999)[101]	RS	63	63	AG+AB	160 (imm)	HA-coated	24–48	100	ND
Keller et al (1999)[44]	RS	37	58	AB	127 (imm) 12 (del)	Machined	12–144	85.6	ND
Khoury (1999)[102]	RS	216	216	AB/AB+HA	467 (imm)	Rough/ Machined	24–72	94	94
Lekholm et al (1999)[46]	RS	68	ND	AB	330 (ns)	Machined	36	77.9	ND
De Leonardis and Pecora (1999)[103]	CCT	57	65	CS	56 (imm) 74 (del)	Rough/ HA-coated	12	98.5	ND
Olson et al (2000)[104]	RCT	29	45	AG+AB/AB/ HA+AG/HA/AG	120 (ns)	HA-coated/ND	6–71	97.5	ND
Mazor et al (2000)[105]	PS	10	10	HA	26 (imm)	HA-coated	12–24	100	ND
Valentini et al (2000)[106]	PS	15	20	BBM	57 (del)	Rough	36–60	98.2	98.2
Lorenzoni et al (2000)[107]	RS	67	ND	AB/BBM	73 (imm) 25 (del), 78 (ns)	Rough	6–60	95	94
Wannfors et al (2000)[108]	RCT	40	80	AB	76 (imm) 74 (del)	Machined	12	84	ND
Kassolis et al (2000)[109]	PS	14	14	AG+PRP	36 (del)	Machined	12	88.9	ND
Raghoebar et al (2001)[110]	RS	99	182	AB	86 (imm) 306 (del)	Machined	12–124	91.8	90.8
Kahnberg et al (2001)[111]	PS	26	39	AB	91 (imm)	Machined	12–72	61.2	ND
Tawil and Mawla (2001)[112]	CCT	29	30	BBM	41 (imm) 20 (del)	Machined	12–40	85.2	ND
Hallman et al (2002)[113]	PS	20	30	BBM+AB	79 (del)	Rough	18	92.4	ND
Hallman et al (2002)[114]	CCT	21	36	BBM/BBM+ AB/AB	111 (del)	Rough	12	91	ND
Engelke et al (2003)[115]	RS	83	118	TCP+AB	175 (imm) 36 (del)	Rough	6–60	94.8	ND
Stricker et al (2003)[116]	RS	41	66	AB	48 (imm) 135 (del)	Rough	15–40	99.5	97.8
Rodriguez et al (2003)[117]	PS	15	24	BBM+PRP	70 (imm)	ND	6–36	92.9	ND
Valentini and Abensur (2003)[118]	RS	59	78	BBM/BBM+AG	55 (imm) 128 (del)	Rough/ Machined	38–113	94.5	ND
McCarthy et al (2003)[119]	RS	19	27	AB+BBM/ AB+PRP/AB	27 (imm) 49 (del)	Machined	19–72	78.9	ND
Philippart et al (2003) [120]	RS	18	25	AB+PRP	58 (del)	Rough	12–48	91.4	ND
Pinholt (2003)[121]	RS	22	39	AB	104 (del)	Rough/ND	20–67	86.5	ND
Hatano et al (2004)[122]	RS	191	361	BBM+AB	361 (imm)	Machined	6–108	94.2	ND
Hallman and Nordin (2004)[123]	RS	50	71	BBM	196 (del)	Rough	6–42	96	96
Hallman and Zetterqvist (2004)[124]	PS	20	30	AB+BBM	79 (del)	Machined	36	88.6	88.6
Shlomi et al (2004)[125]	RS	63	73	AB+BBM/AB	253 (ns)	HA-coated	24	90.9	ND
Simion et al (2004)[126]	RS	14	16	AB+BBM/AB	16 (imm) 22 (del)	Machined	12–84	92.1	76.3

Table 2 continued Sinus Lifting Procedure (Lateral Approach)—Characteristics of Included Studies

Study	Study type	No. of patients	No. of SFE	Grafting material	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival (%)	Implant success (%)
Iturriaga and Ruiz (2004)[127]	RS	58	79	AB	223 (del)	Rough/ Machined/ HA-coated	24–96	100	ND
Velich et al (2004)[128]	RS	624	810	AB+AG/AB	1482 (ns)	Rough/ Machined	60	94.5	ND
Zijderveld et al (2005)[129]	CCT	10	16	AB/TCP	67 (del)	Rough	6–19	100	ND
Rodoni et al (2005)[130]	PS	13	13	BBM	47 (ns)	Machined	37–62	100	100
Butz and Huys (2005)[131]	RS	20	22	AP+AB	48 (imm) 8 (del)	Rough	84	100	100
Wiltfang et al (2005)[132]	RS	61	ND	AB	349 (del)	Rough	54	94.6	ND
Peleg et al (2006)[133]	RS	731	731	AB/DFDBA/ BBM/BBM+AB/ TCP	2132 (imm)	Rough	108	97.9	ND
Galindo-Moreno et al (2007)[134]	RS	70	98	BBM+AB+PRP	48 (imm) 215 (del)	Rough	24	99.0	99.0
Krennmair et al (2007)[135]	RS	37	37	BBM+AB	28 (imm) 12 (del)	Rough	24–66	100	ND
Chen et al (2007)[136]	RS	33	ND	None	47 (imm)	Rough	24	100	ND
Chiapasco et al (2008)[137]	RS	692	952	AB	443 (imm) 1594 (del)	Rough/ Machined	12–144	90–97.6	85.4–95.5
Bornstein et al (2008)[138]	PS	56	59	AB+BBM/ AB+TCP	111 (del)	Rough/ND	60	98	98

RS = retrospective study; PS = prospective study; CCT = controlled clinical trial; RCT = randomized controlled trial; SFE = sinus floor elevation procedures; AB = autogenous bone; AG = allograft; AP = alloplastic material; BBM = bovine bone mineral; PRP = platelet-rich plasma; TCP = tricalcium phosphate; CS = calcium sulfate; HA = hydroxyapatite; DFDBA = demineralized freeze-dried bone allograft; imm = immediate placement; del = delayed placement; ns = implant placement timing not specified; ND = no data.

delayed implants. The authors concluded that there were no significant differences in the survival rates of implants.

Survival Rates of Implants According to Type of Implant Surface. With regard to the survival rates of implants according to type of implant surface, machined-surface implants showed on average lower survival rates (range 61.2% to 100%; mean 88.7%; median 87.5%; 2,431 implants placed, 292 removed) as compared to rough-surfaced implants (range 90.9% to 100%; mean 97.1%; median 98%; 6,249 implants placed, 197 removed). These figures suggest that the roughness of the implant surface may be an important factor in the process of osseointegration of implants placed in grafted sinuses (either with autogenous bone or alloplastic materials) and in the maintenance of crestal bone levels around implants.

Survival Rates of Implants According to Quantity and Quality of Residual Bone. The quantity and quality of residual bone in the posterior maxilla may influence survival rates of implants, independently from the type of grafting procedure. Yet only 43 out of 59 articles reported data on initial residual bone height, and only one article[137] also reported data on residual bone width. It is therefore difficult to know which might be the influence on implant survival—residual bone volume or grafting material. Another parameter that might influence the outcome of implants is the quality of residual bone, but only 6 out of 59 articles reported data on bone quality according to well-defined criteria.[46,95,110,112,117,121]

Discussion. The analysis of the literature seems to demonstrate that maxillary sinus grafting is a reliable surgical technique which permits implants to be placed in the atrophic posterior maxilla with an excellent long-term prognosis. Similar results have been obtained with different grafting materials, such as autogenous bone, allografts, xenografts, alloplastic materials, and mixtures of these materials.

Survival rates of implants placed in grafted sinuses are consistent with those of implants placed in nongrafted edentulous maxillae,[1–10] in particular when rough-surfaced implants are used. However, these results should be interpreted with caution, because the analysis of available publications demonstrated, on average, a poor methodological quality with regard to type of study (the majority were retrospective clinical series), description of the initial clinical situation (quality and quantity of posterior maxilla residual bone), success rate of implants according to well-defined criteria, and duration of follow-up. Moreover, it was frequently difficult or impossible to retrieve pertinent data related to survival of implants because in many articles different materials or different mixtures were used without separating results. All these factors may introduce relevant bias and make statistically significant comparisons difficult. In particular, precise data concerning the initial clinical

situation in the edentulous posterior maxilla (ie, residual bone volume and interarch relationship) should always be reported in publications. This aspect is deemed to be important by the authors of the current review, because different amounts of residual bone prior to sinus grafting procedures may influence the final outcome of implants placed in the grafted areas. In particular, if the residual volume of the posterior maxilla is not described in terms of volume, it is difficult to evaluate if the survival rate of implants placed in the grafted area is related to the support offered by the grafted material or to the residual bone.

It is also worth noting that atrophy of the edentulous maxilla develops tridimensionally, and is not only dependent on sinus pneumatization. Therefore, insufficient bone height may also be related to vertical resorption of the alveolar ridge or a combination of vertical resorption and sinus pneumatization. In the first situation, a sinus grafting procedure may be indicated, whereas in the second (vertical atrophy) it may happen that the sinus does not need to be grafted. Instead, a vertical reconstruction to recreate an adequate interarch distance may be the treatment of choice. Moreover, bone resorption of the edentulous ridge may lead to a horizontal discrepancy between the maxilla and the mandible. If the sinus grafting procedure is the only one performed, it may happen that implants will be placed in a palatal position, with a less-than-ideal prosthetic rehabilitation from an esthetic and functional viewpoint.

Therefore, the atrophic posterior maxilla should be evaluated and classified not only in terms of residual bone height and width, but also vertical and horizontal intermaxillary relationships. Consequently, sinus grafting may represent only a part of the reconstructive procedure necessary to reestablish adequate bone volumes and intermaxillary relationships, to optimize implant placement and the final prosthetic results from a functional and esthetic point of view.

Classifications that consider these parameters should be used when reporting data in order to obtain more homogeneous samples of patients, thus simplifying comparisons of clinical outcomes involving different procedures and/or different grafting materials, such as the classifications proposed by Chiapasco et al[137] and Misch et al.[139] As already stated, only 1 article[137] out of 59 correlated survival and success rates of implants placed in grafted sinuses to the initial clinical situation (ie, residual bone height and width of the posterior maxillary ridge, intermaxillary relationships, distance between the maxillary ridge and opposing dentition, etc).

However, within the limits determined by the lack of some data, some conclusions can be drawn on the following topics.

Safety of Sinus Grafting Procedures. Grafting of maxillary sinuses is accompanied by a very low complication rate. It has been demonstrated that the volume reduction of the maxillary sinus following sinus elevation does not interfere with sinus functions.[140] Intraoperative complications, which are mainly represented by sinus mucosa perforations, are well tolerated and followed by normal recovery in the vast majority of cases. The sinus mucosa will usually regenerate over the bone graft postoperatively. The majority of authors suggest treating perforations either by simply folding the sinus mucosa after a more extended elevation, or with resorbable barriers, such as collagen, fibrin adhesive, or resorbable membranes.[94,100,102,110,112,115,116,118,123,125,129]

Complications such as sinusitis tend to occur in previously unhealthy sinuses.[140] Therefore, a thorough preoperative screening of maxillary sinus status is mandatory (ie, CT scans).

Choice of Grafting Material. Nonautogenous grafting materials appear to be reliable for sinus floor elevation, with no significant differences in clinical outcomes and implant survival. Autogenous bone presents similar results, but it has both advantages and disadvantages, which can be summarized as follows:

- Autogenous bone must be harvested from intraoral or extraoral sites, with higher morbidity as compared to nonautogenous materials (ie, risk of neural disturbances in case of intraoral grafts due to possible lesions of the inferior alveolar nerve branches, and gait disturbances in case of harvesting from the iliac crest).
- When a delayed implant placement is indicated, maxillary sinuses grafted with autogenous bone may receive implants earlier than sinuses grafted with nonautogenous bone substitutes, as demonstrated by the systematic review by Pjetursson et al.[141]
- Autogenous bone is the material of choice when sinus grafting procedures must be associated with onlay grafting of the maxilla in the case of severe atrophy.[40,42,44,46,53,137,142] Conversely, there is a lack of information regarding such reconstructions with nonautogenous materials.

Resorption of Grafts Over Time. It has been demonstrated that grafted sinuses may undergo re-expansion over time, in particular in the first 2 to 3 years after the grafting procedure.[122] The use of nonresorbable or slowly resorbable grafting materials should prevent this phenomenon. If particulated autogenous bone is used, a mixture with xenografts or alloplastic materials, such as BBM or HA, should reduce the risk of bone resorption and sinus repneumatization.[84,87,113,114,122–124]

Table 3 Sagittal Osteotomy—Characteristics of Included Studies

Study	Study type	No. of patients	Defect site	Grafting material	Surgical success (%)	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival %	Implant success %
Engelke et al (1997)[144]	RS	44	Maxilla	HA+e-PTFE	100	124 (imm)	Machined/Rough/ HA-coated	6–68	91	86.2
Bruschi et al (1998)[145]	RS	303	Maxilla	CLS	100	499 (imm)	Rough	25–60	ND	97.5
Sethi and Kaus (2000)[146]	RS	150	Maxilla	None	ND	449 (imm)	ND	1–93	97	ND
Chiapasco et al (2006)[147]	PS	45	Max/Mand	None	98	110 (imm)	Rough	12–36	97.3	95.4

RS = retrospective study; PS = prospective study; Max = maxilla; Mand = mandible; CLS = collagen sponge; Surgical success = success rate of the surgical procedure; HA = hydroxyapatite; imm = immediate placement; ND = no data.

Timing of Implant Placement. Both immediate implant placement (in conjunction with grafting procedures) and delayed implant placement (after consolidation of the graft has occurred) have been proposed. Although it is impossible to determine a clear indication for immediate or delayed implant placement, the majority of authors agree in suggesting immediate implant placement when the residual alveolar bone presents adequate quality and quantity to allow primary stability of implants. In general, immediate placement is not indicated when the residual height is less than 4 to 5 mm, and in cases of poor bone quality. Tawil and Mawla[112] demonstrated that immediate implant placement with less than 5 mm residual bone height is followed by significantly lower implant survival rates than placement in more than 5 mm residual bone (56% versus 100%). A previous review of the literature concerning this topic[142] showed lower survival of implants placed in conjunction with the grafting procedure. Only one article reported a successful outcome of implants placed in conjunction with the grafting procedure with a very limited residual bone height (1 to 2 mm).[93] However, no clear indications were found in the literature.

Survival of Implants According to Type of Implant Surface. In the studies analyzed in this review, both machined-surface implants and rough-surfaced implants were used. Regardless of the technical process used to roughen the surface, implants with rough surfaces demonstrated a mean survival rate significantly higher than machined-surface implants (96.9% and 88%, respectively). These results have also been confirmed by a recent systematic review by Pjetursson et al[141]: The authors concluded that statistically significantly higher survival rates were obtained when rough-surfaced implants were inserted, irrespective of the grafting material used.

Loading Time of Implants Placed in Grafted Areas. Implants placed in grafted sinuses were loaded 2 weeks to 13 months afterwards (on average 5 to 6 months after). It is difficult to give clear indications, however, because osseointegration and implant capability to withstand the functional demands of loading are influenced by a large number of factors, including residual bone volume before the grafting procedure, quality of residual bone, type of grafting material, implant dimensions, implant macro- and microgeometry, type of implant surface, type of prosthesis, and type of opposing arch dentition. These considerations were already addressed by Jensen et al[143] in their review on sinus grafting procedures. Since then, no significant information has been added. Therefore, studies addressing these topics are needed.

One of the few aspects which seems to be clarified is that screw-shaped implants with rough surfaces offer a better prognosis than implants with machined surfaces,[143] but data have been retrieved mainly from retrospective studies and not from prospective, comparative studies.

Bone Splitting/Expansion and Immediate Implant Placement

Patients and Methods. The search identified 387 publications, 32 of which were screened as full-text articles. A total of 4 studies were selected.[144–147] Of these, 3 were retrospective clinical studies and 1 was a prospective multicenter clinical study. Overall, 542 patients were treated with bone splitting/expansion of narrow edentulous ridges and immediate placement of implants. A total of 1,182 implants were placed in the expanded edentulous sites at the time of the expansion procedure. The gap created by splitting was either left empty or filled with different materials, such as collagen sponge, BBM, autogenous bone chips, and HA. In one study the interposed grafting material was covered with e-PTFE membranes.[144] Dental rehabilitation with removable or fixed implant-supported prostheses was started 3 to 6 months afterwards. Patients were followed from 1 to 93 months after the start of prosthetic loading (Table 3).

Outcomes. Success rates of the surgical procedures ranged from 98% to 100%. Fracture of the buccal plate was the most common complication.

Implant survival rates ranged from 91% to 97.3% (median 94%), while success rates ranged from 86.2% to 97.5% (median 95.5%) (Table 3).

Discussion. Bone splitting/expansion seems to be a reliable and relatively noninvasive technique to correct narrow edentulous ridges. Survival and success rates of implants placed in the expanded ridges are consistent with those of implants placed in native, nonreconstructed bone. The gap created by sagittal osteotomy/expansion undergoes spontaneous ossification, following a mechanism similar to that occurring in fractures. New bone formation permits a consolidation between the oral and buccal bone plates of the alveolus, and implants placed in expanded ridges seem to withstand the biomechanical demands of loading. However, some considerations have to be made.

Bone splitting/expansion can be applied only when the buccal and palatal/lingual plates are separated by spongy bone. Therefore, the indications are more limited as compared to onlay grafts and GBR, which can be also applied in cases presenting with severe horizontal atrophy.

Another limitation is represented by unfavorable inclination of implants placed in expanded areas. This procedure may lead to excessive buccal inclination of implants, which may create problems from a functional and esthetic viewpoint. In the case of unfavorable bone angularity, GBR or bone grafting techniques seem to represent more adequate surgical procedures.

The significantly higher number of maxillary expansion procedures is explained by the fact that maxillary ridges, due to the lower bone density and thinner cortical buccal plate, are more easily treated than mandibular ridges. Mandibular sagittal osteotomy, although possible, is more difficult due to the denser bone of the buccal plate, as demonstrated by some authors.[147] Drawbacks of this anatomical condition include greater difficulty in expanding, the risk of a more invasive and more traumatic surgical procedure, and the risk of buccal plate fracture.

Although implant survival rates are comparable to those obtained in cases of implants placed in native nonaugmented bone, a paucity of data is available with regard to the stability over time of the initial bone volume obtained after expansion. Only one out of four articles[147] evaluated horizontal bone changes with the aid of surgical calipers, resulting in a median value of 0.5 mm (range 0.5 to 1.5 mm) 3 years after the start of prosthetic loading. It is therefore recommended that future reports address this aspect.

Split-Ridge Techniques with Interpositional Bone Grafts and Delayed Implant Placement

Patients and Methods. Of the initial articles retrieved (374), 6 were screened as full text, but none fulfilled the criteria for inclusion. Therefore, although this procedure has been described in the literature, there are no available data due to insufficient sample size and/or follow-up.

Vertical Distraction Osteogenesis

Patients and Methods. Of the initial 128 articles retrieved, 44 were screened as full text and 7 were considered suitable for inclusion.[148–154] Four of these were prospective clinical studies and 3 were retrospective studies. A total of 181 patients presenting with vertical resorption of partially or totally edentulous alveolar ridges were treated with distraction devices. Both intraoral intraosseous devices and intraoral extraosseous devices were used (see Table 4 for details). The rate of distraction per day ranged from 0.5 to 1.6 mm.

A total of 462 implants were placed, 62 of which served both as intraoral intraosseous distraction devices and as definitive implants for prosthetic restorations. Four hundred implants were placed 2 to 3 months after the completion of distraction, once sufficient maturation of the bone in the distraction gap had occurred.

Prosthetic rehabilitation was started 3 to 6 months after implant placement. Both fixed and removable implant-supported prostheses were used, but only two articles reported adequate information on prosthetic rehabilitation. Follow-up after the start of prosthetic loading ranged from 6 to 72 months (Table 4).

Outcomes. Postoperative recovery after distraction was uneventful in 73% of patients. Minor complications included change of the distraction vector (successfully corrected during distraction with prosthetic/orthodontic appliances) (8.3%), incomplete distraction (2.2%), fracture of the distraction device (1.6%), transient paresthesia in the innervation area of the mandibular nerve (1.6%), and partial relapse of the initial bone gain (7.7%), which nevertheless permitted implant placement after further minor augmentation procedures (it is worth noting that this complication occurred only in patients treated with intraoral/intraosseous devices). Total failure of the procedure was reported in only 2 out of 181 patients (1.1%), whereas major complications such as basal bone fracture and fracture of the distracted bone occurred in 5 patients (2.7%) but were successfully treated and had no consequences as far as the completion of the planned treatment was concerned. Therefore, the overall success rate of the procedure was 98.9%. (Gaggl et al 2000[148] did not report data on complications.)

Table 4 Vertical Distraction Osteogenesis—Characteristics of Included Studies

Study	Study type	No. of patients	Defect site	Type of device	Distr success (%)	Bone gain (mm)	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival %	Implant success %
Gaggl et al (2000)[148]	PS	34	Max/Mand	Intraoral/ Intraosseous	ND	3–6	62 (imm)	Rough/ Machined	12	96	ND
Rachmiel et al (2001)[149]	RS	14	Max/Mand	Intraoral/ Intraosseous	97	8–13	23 (del)	Machined	6–20	100	ND
Raghoebar et al (2002)[151]	PS	10	Mand	Intraoral/ Intraosseous	100	6–8	20 (del)	Rough	6–20	95	ND
Jensen et al (2002)[150]	PS	28	Max/Mand	Intraoral/ Intraosseous Intraoral/ Extraosseous	96.7	4–15	84 (del)	Rough	12–60	90.4	ND
Chiapasco et al (2004)[152]	PS	37	Max/Mand	Intraoral/ Extraosseous	97.2	4–15	138 (del)	Rough/ Machined	15–55	100	94
Enislidis et al (2005)[153]	RS	37	Mand	Intraoral/ Intraosseous Intraoral/ Extraosseous	57.8	5–15	93 (del)	ND	6–58	95.7	ND
Uckan et al (2007)[154]	RS	21	Max/Mand	Intraoral/ Intraosseous Intraoral/ Extraosseous	95.8	5–20	42 (del)	ND	8–72	88–94	ND

RS = retrospective study; PS = prospective study; Max = maxilla; Mand = mandible; Distr success = success rate of the distraction procedure; imm = immediate placement; del = delayed placement; ND = no data.

The vertical bone gain obtained at the end of the distraction period ranged from 3 to 20 mm.

Of 462 implants placed, 19 were removed (14 preload, 1 postload, and 4 nonspecified), with an overall survival rate of 95.9% (range 88% to 100%; median 95.5%). All failures occurred in the group in which intraoral intraosseous devices were used.

Success rate according to well-defined criteria[1] was reported only in one article[152] in which no implants (out of 138) were lost, but 8, although osseointegrated, presented peri-implant bone resorption rates higher than those proposed for successful implants, resulting in a success rate of 94.2% (Table 4).

Discussion. Despite the limited number of patients and implants placed in the retrieved articles, the following conclusions can be drawn:

- Distraction osteogenesis provides an opportunity to obtain a natural formation of bone between the distracted segment and basal bone in a relatively short time span, thus avoiding the necessity of autogenous bone harvesting. This leads to a reduction of morbidity and a shortening of operating times. Soft tissues can follow the elongation of the underlying bone (neohistogenesis), and there is a lower risk of infection of the surgical site (0% in this case series). Both limited and extended (fully edentulous patients) defects can be treated.
- Histologic results seem to demonstrate that distraction osteogenesis allows the formation of adequate quality and quantity of bone tissue, which can provide primary stability of implants and favorably withstand the biomechanical demands of loaded implants. Biopsies taken at the time of implant placement, after consolidation of the distracted area,[151,155–159] demonstrated that distraction is able to induce the formation of new bone that matures similarly to natural bone.
- Survival and success rates of implants placed in distracted areas are consistent with those reported in the literature for implants placed in native, nonregenerated/reconstructed bone.[1–10]

However, some disadvantages of vertical distraction osteogenesis must be emphasized:

- Frequent lingual/palatal inclination of the distracted segment has been reported by some authors, with an incidence varying from 13% to 35.4%,[148–154] probably due to local muscle pull, inappropriate device positioning, and/or poor device trajectory. To solve this complication, different solutions have been suggested, including the use of fixed or removable prosthodontic and orthodontic devices to guide the distracted segment to its proper final position. Ideally, a multidirectional alveolar distraction device would allow the vector to be modified and guided in several planes of space. Some authors[160,161] reported their experience with such a device, resulting in a reduced incidence of distracted

Table 5 Le Fort I Osteotomy with Inlay Grafts—Characteristics of Included Studies

Study	Study type	No. of patients	Donor site	Success proc (%)	No. of implants (timing)	Implant surface	Follow-up (mo)	Implant survival (%)	Implant success (%)
Isaksson et al (1993)[164]	RS	12	Ilium	100	59 (imm)	Machined	12–24	79	ND
Cawood et al (1994)[165]	RS	12	Ilium+HA	92	64 (del)	Rough/Machined	12–36	67–95	ND
Krekmanov (1995)[166]	RS	35	Ilium	95	225 (imm)	Machined	12–48	87	ND
Li et al (1996)[167]	RS	20	Ilium	100	139 (imm)	ND	13–62	82	ND
Watzinger et al (1996)[168]	RS	11	Ilium	91	41 (imm) 35 (del)	Rough	30	88	81
Nyström et al (1997)[169]	RS	10	Ilium	100	60 (del)	Machined	15–39	95	ND
Keller et al (1999)[78]	RS	10	Ilium	100	8 (imm) 45 (del)	Machined	6–139	83	ND
Kahnberg et al (1999)[170]	RS	25	Ilium	100	181 (del)	Machined	60	83	ND
Lekholm et al (1999)[46]	RS	20	Ilium	ND	133 (imm)	Machined	12–36	80	ND
Stoelinga et al (2000)[171]	RS	15	Ilium+HA	100	92 (del)	Rough/Machined	12–144	91	91
Yerit et al (2004)[172]	RS	30	Ilium	90	276 (imm)	Rough	12–120	87–91	ND
Hallman et al (2005)[173]	RS	22	Ilium	100	156 (del)	Rough	60	87–94.5	52–70
Chiapasco et al (2007)[174]	PS	39	Ilium	97.5	281 (del)	Rough	12–108	94.5	82.9

RS = retrospective study; PS = prospective study; HA = hydroxyapatite; Success proc = success rate of the procedure; imm = immediate placement; del = delayed placement; ND = no data.

segment malposition, but short follow-ups and lack of sufficient information concerning the success rates of implants placed in the distracted areas do not allow significant conclusions to be drawn.

- The majority of authors reported some relapse of initial bone gain, before implant placement, due to marginal bone loss of the most coronal part of the distracted segment. Therefore, a 20% overcorrection was suggested by one group.[162] Conversely, crestal bone changes around implants after the start of prosthetic loading seem to be similar to those occurring in cases of implants placed in native, nonreconstructed bone, as demonstrated by experimental and clinical studies.[149,150,152,156]
- As compared to other augmentation procedures, such as GBR or bone grafting, vertical distraction does not allow simultaneous correction of narrow ridges, which is only possible with overdistraction of the segment and secondary height reduction until adequate bone width is obtained. However, overcorrection may lead to surrounding soft tissue tears and/or ischemia. The second possibility is secondary bone grafting at the time of distraction device removal,[163] but this procedure eliminates one of the main advantages of alveolar distraction, which is that there is no need for bone harvesting.
- As compared to GBR and grafting procedures, which can be applied both for mandibular and maxillary defects, vertical distraction seems to be more indicated in the correction of mandibular defects. This may be related to difficulties in maintaining an adequate vector in the maxilla, due to inextensibility of palatal fibromucosa. Also, maxillary sinus pneumatization can preclude the possibility of distraction osteogenesis due to insufficient bone height to perform the osteotomy.

Le Fort I Osteotomy with Interpositional Autogenous Bone Grafts

Patients and Methods. The search identified 679 articles. Of these, 31 were screened as full text and 13 were selected[46,78,164–174] (Table 5). Twelve of the selected studies were retrospective clinical studies and 1 was a prospective multicenter clinical study.

A total of 261 patients affected by extreme atrophy of the edentulous maxilla (class VI according to the Cawood and Howell classification [1988][63]) were treated with Le Fort I osteotomy and inlay bone grafts taken from the anterior iliac crest, to correct not only alveolar bone deficiency but also severe intermaxillary discrepancy. One hundred twenty-four patients received 881 implants placed during the same surgical session (6 to 9 implants per patient), while 137 patients received 914 implants in a second stage, after consolidation of the graft occurred (3 to 12 months after reconstruction). A total of 1,795 implants were placed in the reconstructed maxillae. Prosthetic rehabilitation was started 4 to 12 months after implant placement. Both fixed and removable implant-supported prostheses were used for the rehabilitation of treated patients (3 of 13 articles did not report data on prosthetic rehabilitation[46,165,166]). Follow-up after the start of prosthetic loading ranged from 6 to 144 months (Table 5).

Outcomes. Postoperative recovery after Le Fort I osteotomy was uneventful in the majority of patients. In four patients, intraoperative fracture of the palate occurred but with no consequences on the final outcome. In seven patients, postoperative sinusitis occurred, but was successfully treated with antibiotics. In seven patients, minor dehiscence with moderate bone graft fragment exfoliation was reported, with no consequences on the following rehabilitation phases.

In seven patients, dehiscence with partial bone loss/infection occurred, but prosthetic rehabilitation, despite having to be modified, was concluded successfully. A total failure of the procedure was reported only in one patient. The overall complication rate of this surgical procedure was 3.1% (range 0% to 10%).

Of 1,795 implants placed, 218 were removed (overall survival rate 87.9%; range 66.7% to 95%; median 87%). One hundred twenty-five implants were lost in the group where implants were placed in conjunction with Le Fort I osteotomy (881 implants), while 83 were lost in the group in which implants were placed at a second stage (914 implants). An additional 9 implants were lost in one study where both immediate and delayed implants were placed,[78] but it was not reported in which of the two groups of implants these losses occurred.

With regard to implant surface, a lower survival rate was observed for machined-surface implants (range 79% to 95%; mean 84.5%; median 83%; 108 implants removed out of 711 placed) compared to rough-surfaced implants (range 82% to 94.5%; mean 90.3%; median 89.5%; 65 implants removed out of 789 placed).

Implant losses occurred both before and after the start of prosthetic loading, but again data are incomplete and it was not possible to specify the exact time distribution of losses.

The survival rate of implants placed in conjunction with the reconstructive procedure was 85.8% (range 79% to 95%; median 84.5%; mean 84.3%). For implants placed in a staged approach, the survival rate was 90.9% (range 66.7% to 95%; median 93%; mean 88.4%). No well-defined implant success criteria were found in the majority of articles, with only three publications[167,171,174] reporting 88.1%, 91%, and 82.9% success rates according to well-defined criteria (Table 5).

Discussion. The analysis of the available publications demonstrated on average poor methodological quality with regard to completeness of follow-up and success criteria of implants. Despite these limits, the following observations can be made:

- Le Fort I osteotomy in association with interpositional bone grafts and immediate or delayed implant placement is a reliable, albeit demanding, procedure that should be limited to severe maxillary atrophy associated with unfavorable intermaxillary relationship. In these situations, techniques such as onlay bone grafting, even if they can recreate adequate bone volumes for implant placement, may not be able to correct an inadequate intermaxillary relationship; this might lead to an inadequate final prosthetic outcome from a functional and/or esthetic viewpoint.
- The procedure is associated with relevant, albeit temporary, postoperative morbidity. Pain and hip-related discomfort were observed in almost all patients but were transient in the majority of cases.
- Partial or total failure of the grafting procedure is very limited (3.1%). Some authors[166,172] consider the preservation of the sinus mucosa a critical factor for reducing this complication, although others reported a 100% success rate of the grafting procedure despite total removal of the sinus mucosa.[78,164,169]
- Survival rates of implants placed in the reconstructed maxillae are, on average, lower (range 66.7% to 95%; mean 87.9%) than those reported for implants placed in native bone. However, it is worth noting that when only rough-surfaced implants are considered, survival rates of implants, although lower, compare favorably with those of implants placed in native maxillary bone (overall survival rate of rough-surfaced implants 91.8%; range 87% to 94.5%).
- The choice of implant placement timing is still controversial, because some authors prefer simultaneous placement[46,164,166,167,172] while others prefer implant placement after graft consolidation.[165,169,170,171,174] Although statistically significant data are difficult to obtain, survival rates were higher for patients receiving implants after the reconstructive procedure than for those receiving implants simultaneously (93% and 84.5% median values, respectively).
- None of the authors proposed immediate loading of implants placed in the reconstructed maxillae.
- No indications have been found concerning the choice of length and diameter of implants placed in the reconstructed areas, although a tendency toward longer implants that can engage the entire volume of the grafted bone has been observed. In fact, a higher failure rate was found with shorter implants.[78,166] On average, six to eight implants per patient have been suggested, but no specific indications concerning the number of implants to be placed were found.

CONCLUSION

This literature review has demonstrated that a wide range of surgical procedures can be used to correct deficient edentulous ridges. On the basis of available data, it is difficult or impossible to determine that one surgical procedure offers a better outcome than another, as far as predictability of the augmentation and survival/success rates of implants placed in the

augmented sites are concerned. Every surgical procedure presents advantages and disadvantages, which must be carefully evaluated before surgery. Moreover, it is not yet known if some surgical procedures that are widely used in clinical practice, such as sinus grafting procedures in the case of limited/moderate sinus pneumatization or reconstruction of atrophic edentulous mandibles with onlay autogenous bone grafts, are really useful for improving the long-term survival of implants.

However, despite recommendations in previous review papers[30,31] for better-designed studies according to the Consolidated Standards of Reporting Trials (CONSORT) guidelines,[175] the main limitation encountered in this literature review was the overall poor methodological quality of the published articles; this may reduce the possibility of drawing significant conclusions.

As suggested by Esposito et al,[30] in order to understand when bone augmentation procedures are needed and which are the most effective techniques for the specific clinical indications, larger, well-designed, long-term trials are needed. It was also stated that it is difficult to provide clear indications with respect to which procedures are actually needed. Priority should be given to procedures that are simpler and less invasive, involve less risk of complications, and reach their goals within the shortest time frame.

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