Pre-Implant Surgery

Volumetric osseous changes in the completely edentulous maxilla after sinus grafting and lateral bone augmentation: a systematic review

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Abstract. The aim of this systematic review was to evaluate the volumetric changes associated with different bone grafting techniques in the completely edentulous atrophic maxilla before dental implant placement. A search was performed according to the PRISMA guidelines. A PICO question was formed, and the PubMed, Scopus, Embase, and Cochrane Library databases were searched, covering the period 2000–2018. Relevant data were extracted from the results regarding study population, surgical details, technical information on volumetric data acquisition, and volumetric outcome after bone augmentation procedures before implant placement. Six articles with a combined population of 84 patients were included. All patients had a completely edentulous maxilla, with a crestal horizontal width of <3–4 mm or a crestal vertical height of <6–7 mm. The iliac bone and ascending ramus were most frequently used as grafts. Five of the six studies reported volumes of sinus inlay graft (SIG) and four reported volumes of lateral bone augmentation (LBA). Radiographic analyses of the augmented areas differed among the studies. Volume loss after bone augmentation procedures ranged from 5% to 50% for SIG and from 5% to 47% for LBA. All surgical augmentation techniques for the edentulous maxilla are prone to resorption; no procedure seemed to be superior, but some interesting observations were made.

Key words: edentulous maxilla; maxillary atrophy; bone graft; volumetric change; dental implant.

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Following the removal of teeth as a result of infectious disease or trauma, the alveolar bone undergoes resorption. The process of

alveolar bone resorption, classified by Cawood and Howell, can result in adverse effects, such as the loss of prosthetic support

and retention and loss of soft tissue support of the upper lip, as well as having an impact on vertical facial dimensions^{1–3}.

Multiple surgical procedures have been developed to improve the configuration of the alveolar ridge in order to overcome these adverse effects. Surgery can encompass procedures including the soft tissues (e.g., vestibuloplasty)^{4,5} and/or the bony tissues, or refer to a dental prosthesis solution (e.g., sub-periosteal prosthesis)⁶.

Historically, the use of soft tissue procedures has diminished due to the rise of dental implants. Dental implants in combination with adequate prosthetics represent a major advancement in both functional and aesthetic rehabilitation of the atrophic maxilla. An important prerequisite is the availability of a bony envelope in which the dental implants can be placed. Another prerequisite is good primary dental implant stability, which requires an alveolar bone height of at least 5 mm on average⁷.

When the alveolar process lacks these minimal dimensions, bone augmentation procedures can be considered. The main goal is to create a stable base for implant placement to restore dental and aesthetic functions prosthetically. Four types of maxillary reconstruction are usually described in the literature: sinus inlay grafts (SIG), lateral bone augmentation (LBA)/buccal onlay grafts, vertical onlay grafts, and interpositional grafts^{1,8-10} (Fig. 1).

Several studies and systematic reviews have been conducted to evaluate the quality of specific bone grafts and surgical procedures¹¹⁻¹³. There is considerable heterogeneity in the literature both in surgical techniques and in study populations, making the comparison of results between studies difficult.

The general conclusion throughout the literature has been that all bone grafting procedures are prone to some resorption before dental implant placement. Most of the bone resorption and volumetric loss takes place in the period immediately after the augmentation procedure and before the placement of dental implants¹⁴.

Regarding the study population, it is difficult to assume that LBA for the placement of a single implant in the anterior region (regardless of the use of particulate or cortical bone) is comparable to a SIG in a partially edentulous jaw or with the augmentation of a completely edentulous jaw. Although a subpopulation with a completely edentulous maxilla has often been included in major studies¹⁴⁻¹⁷, information on volumetric changes after bone augmentation procedures in this patient population, as a separate group, remains scarce.

Epidemiological studies have shown that total edentulism in comparison to partial edentulism is associated with factors such as low income, age, education, and access to dental care¹⁸. With older age, changes in bone metabolism also become a factor. Studies have shown that bone turnover and neovascularization is different in the elderly in comparison to younger individuals¹⁹. According to Klijn et al., an increase in patient age is associated with a reduction in bone graft resorption²⁰.

The presence of occlusal relationships in partially edentulous patients is another reason for differentiating between patients who are completely or partially edentulous. Occlusal relationships give a signifi-

cant advantage to partially edentulous patients in preventing occlusal stress on the grafts after LBA procedures. The immobilization and fixation of LBA remains an important consideration in order to allow vascular ingrowth within the graft and to enable osseointegration^{21,22}.

The arguments above highlight that a completely edentulous study population seems to show different characteristics in comparison to a partially edentulous study population. The aim of this systematic review was to evaluate the resorption rate of the augmented bone volume in the completely edentulous atrophic maxilla from the moment of the surgical grafting procedure until dental implant placement.

Materials and methods

Systematic literature search

The English-language literature was searched for studies containing scientific data on volumetric changes of bone augmentation procedures in the edentulous maxilla. The search strategy was performed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines²³. Search strings with different sets of key words following the PICO criteria were formulated and used to search the PubMed, Embase, Scopus, and Cochrane Library databases. The PICO question was formulated as follows: P = patients with a completely edentulous maxilla, I = bone augmentation procedure, C = not applicable, and O = volumetric bony changes from grafting procedure until dental im-

Fig. 1. Diagrams of the atrophic maxilla, depicting the different surgical procedures and definitions (left, frontal view; right, axial view).

Fig. 2. Flowchart summarizing the search strategy, and the number of studies finally included in the analysis following the selection process using the PubMed, Embase, Cochrane Library, and Scopus databases.

plant placement. The methodology and terms used in the search strategy are illustrated in Supplementary Material File 1.

An extensive search was conducted using the predetermined criteria. In the initial search, articles were selected based on title. After the removal of duplicates, the abstracts of these articles were screened. The remaining articles were investigated for relevance. The main focus of the search was volumetric changes after bone augmentation procedures for the edentulous maxilla. The references in each selected publication obtained from the electronic search were screened manually to check for other eligible articles. The search was limited to studies in the English-language literature and those published between the year 2000 and December 2018. Radiographic volumetric analysis studies published before 2000 were considered out of date. A final search of the literature was completed in December 2018. A flowchart summarizing the search strategy is given in Fig. 2.

Study eligibility

All studies had to meet the following inclusion criteria: (1) involve a study population of patients with a completely atrophied edentulous maxilla, which could be classified as Cawood stage IV–VI; (2) history of surgical bone augmentation procedures performed in the completely edentulous maxilla: sinus inlay grafts (SIG), lateral bone augmentation (LBA)/buccal onlay grafts, vertical onlay grafts, interpositional grafts; (3) contains clear data about volumetric osseous changes after surgical augmentation procedures. The exclusion criteria were animal studies and publications not written in English. Many studies contained information about volumetric changes after bone augmentation procedures in completely edentulous patients and partially edentulous patients combined. Furthermore, many studies included populations in which maxillae and mandibles were treated. Studies from which the maxillary bone augmentation volumetric data from the completely eden-

tulous population could not be uniformly extracted were excluded.

Data extraction process

Two independent reviewers (R.C. and H. G.) conducted the screening process for articles and reviewed the eligibility of retrieved articles. Any disagreement was resolved by consultation with two additional reviewers (T.H. and J.F.).

The following data were extracted from the included studies: authors, year of publication, population inclusion and exclusion criteria, surgical details, data concerning dental implants, technical information on volumetric data acquirement, and volumetric outcome after bone augmentation procedures before dental implant placement. For some articles, the corresponding author was contacted to verify that the study population was completely edentulous and to supplement any missing data from the original study. All articles were made consistent by adjustment to the European metric system,

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Table 1. Characteristics of the study populations.

Author	Population	Age (years) Mean $\pm$ SD Median (range)	Inclusion criteria	Exclusion criteria	Smoking
Dasmah et al. (2012) ²⁹	All: $n = 11$ M: $n = 0$ F: $n = 11$	NM	Edentulous	NM	NM
Dreiseidler et al. (2016) ²⁷	All: $n = 14$ M: $n = NM$ F: $n = NM$	59 ± 12	1. Ant: CVH <7 mm and/or CHW <3 mm 2. Post: CVH <5 mm Cawood–Howell class IV, V, VI CVH <7 mm and/or CHW <6 mm	NM	ND ^a
Hernández-Alfaro et al. (2013) ²⁶	All: $n = 14$	51 (46–68)	Edentulous: Cawood–Howell IV, V	Smoking, previous radiotherapy, refusal to provide written informed consent	Non-smoking, 14
Johansson et al. (2001) ²⁸	M: $n = 4$ F: $n = 10$ All: $n = 10$	58 (49–71)	1. Ant: CVH <6 mm and CHW <4 mm 2. Post: CVH <6 mm Edentulous	NM	Non-smoking, 4
Klijn et al. (2012) ²⁰	M: $n = 3$ F: $n = 7$ All: $n = 20$		1. Ant: Cawood–Howell IV 2. Post: Cawood–Howell V, VI Edentulous for 10 years	NM	Smoking ^b , 6
Xavier et al. (2015) ³⁰	M: $n = 8$ F: $n = 12$ All: $n = 15$	M: 56 ± 14 M: 56 ± 8 54 ± 5 (48–60)	Edentulous	ASA 3 or 4, drug abuse, active periodontitis in the mandible	Non-smoking, 15
	M: $n = 8$ F: $n = 7$		Post: CVH <3 mm		

Ant, anterior; ASA, American Society of Anesthesiologists status; CBCT, cone beam computed tomography; CHW, crestal horizontal width; CVH, crestal vertical height; F, female; M, male; ND, not described; NM, not mentioned; Post, posterior; SD, standard deviation.

^a Described but not distinguishable in the original study population²⁷.

^b 1–20 cigarettes/day.

with volume expressed in cubic centimetres (cm³). The coefficient of variation (CV) for the volume of interest (VOI) over time was calculated using the following formula: $(V_n - V_{n-1})/V_{n-1} \times 100$. Both the volumetric measurements and CV values were rounded up for comparability between the different studies.

Critical appraisal of individual studies

Two authors (R.C. and H.G.) independently assessed the risk of bias for each study using the criteria proposed in the Meta-Analysis of Observational Studies in Epidemiology statement²⁴, Strengthening the Reporting of Observational Studies in Epidemiology statement²⁵, and PRISMA statement²³. Any disagreements were resolved by discussion or by involving two additional authors (T.H. and J.F.) to adjudicate. When two or more domains were missing, the study was considered to have a high risk of bias. A study that included all domains was classified as having a low risk of bias, whereas a study that lacked

one of the domains was classified as having a moderate risk of bias.

Results

After the selection procedure, six articles describing six studies that met the inclusion criteria remained. Two of these studies were prospective^{26,27}, two were retrospective^{20,28}, and two were clinical trials^{29,30}. The inclusion and exclusion criteria of the populations were defined in all of the studies, as were the research questions. No validated tool for measurement of the data was reported in the articles. Five studies had a high risk of bias and one study had a moderate risk of bias (Supplementary Material, File 2).

The two clinical trials had a split-mouth design. After randomization, one side of the maxilla (left or right) acted as the control site and the other as the test site. For both studies, the data for the control and test sites could easily be extracted from the published results^{29,30}.

No studies on vertical bone augmentation procedures or interpositional grafts could be included.

Population specifications

The mean or median age of the study population in all of the studies was >50 years (Table 1). Overall, there were 84 patients in total, with a predominance of female patients. The study populations consisted of patients with a completely edentulous maxilla (Cawood–Howell classification of IV or higher) with a crestal horizontal width (CHW) <3–4 mm or crestal vertical height (CVH) <6–7 mm. One study included patients with CVH <3 mm³⁰ (Fig. 1).

Radiological volumetric analysis

Volumetric data were acquired through radiographic analysis (computed tomography (CT) scan or cone beam CT (CBCT)) and were expressed in cubic centimetres (cm³) (Table 2). Generally, three types of

Table 2. Technical measurement specifications.

Author	Radiographs	Technical specifications	Analysis	Measurements
Dasmah et al. (2012) ²⁹	CT Pace Plus (General Electric, USA)	Distance axial scans = 2 mm Contiguous scan	1. Number of investigators = 1 2. Software: NM 3. Manual search of 3 random CT sections (axial or coronal) each showing the largest amount of bone (test and control group) in all dimensions VOI = CVH × CHW × CHL	1. Manual linear measurement of CVH, CHW, or CHL in selected CT sections 2. Calculation mean for CVH, CHW, and CHL 3.
Dreiseidler et al. (2016) ²⁷	Galileos CBCT (Sirona)	512 pixels Resolution of 300 µm	1. Number of investigators = NM 2. Software: SKY-PlanX (Bredent) 3. Automatic alignment of PE and PO CBCT scan	Augmented areas outlined on axial scans and multiplied by height
Hernández-Alfaro et al. (2013) ²⁶	CBCT (i-CAT, Imaging Sciences International)	120 kV, 5 mA Axial slice distance 0.300 mm ³ Field of view: 23 cm	1. Number of investigators = NM 2. Software: SimPlant Pro Crystal (Materialise) 3. Plane through both infra-orbital foramina and spina nasalis posterior 4. Modification of CBCT threshold grey limits	1. VOI = volume caudal of marked plane 2. VOI calculated from 'Mask list window' SimPlant software
Johansson et al. (2001) ²⁸	CT Pace Plus (General Electric, USA)	Distance axial scans = 2 mm Contiguous scan	1. Number of investigators = 1 2. Scan parallel to palatal plane 3. Software: 9.0 Denta2 Scan	1. Threshold bone = HU >150 2. VOI = $\sum$ (CHW × CHL × 2 mm) ^a
Klijn et al. (2012) ^{20,b}	CBCT (i-CAT, Imaging Sciences International)	120 kV, 3–8 mA (pulse mode) Focal spot: 0.5 mm Field of view: 16 × 22 cm Voxel size: 0.4 mm ³ 0.25 mm slice reconstruction	1. Number of investigators = 1 2. Software: CT-Analyzer V1.10 3. Reslicing in coronal sections (section thickness 0.265 mm)	1. Threshold = grey value >110 2. Augmented area manually drawn through consecutive coronal sections Software calculated VOI
Xavier et al. (2015) ³⁰	CBCT (i-CAT, Imaging Sciences International)		1. Number of investigators = NM 2. Software: Mimics 8.13	VOI = NM

CBCT, cone beam computed tomography; CHL, crestal horizontal length; CHW, crestal horizontal width; CT, computed tomography; CVH, crestal vertical height; HU, Hounsfield units; NM, not mentioned; PE, preoperative; PO, postoperative; VOI, volume of interest.

^a Additional information acquired from former publications by the same author.

^b Additional information acquired through e-mail contact with the corresponding author.

VOI calculation could be defined (Fig. 3A–C, Table 2).

The most frequently used method was outlining the augmented area on the CT scan for each consecutive slice^{20,27,28}. Nonetheless, all authors used different types of parameters in comparison to each other (Fig. 3A).

One study group selected three random CT axial and coronal sections showing the largest CVH, CHW, and crestal horizontal

length (CHL). Only the sections showing the largest amount of bone in all dimensions were used. The mean values were calculated for CVH, CHW, and CHL, based on three measurements. The VOI was calculated by computing the three mean values, resulting in a volumetric rectangle (Fig. 3B)²⁹.

Another research group used a completely different third approach, applying SimPlant software (Materialise,

Belgium): the VOI was the maxillary volume caudal to the marked plane through both the infra-orbital foramina and spina nasalis posterior (Fig. 3C)²⁶. This was the only research group to report a preoperative volume of the maxilla; on the other hand, no clear division could be made between LBA and SIG procedures.

The final group used Mimics software (Materialise, Belgium) to calculate the

Fig. 3. (A) Volume of interest (VOI) calculation according to Johansson et al.²⁸ (2002). The outline of the sinus inlay graft and lateral bone augmentation graft on each scan was plotted and the area calculated automatically. The VOI was calculated by multiplying these areas by the height of each radiographic slice (2 mm). (B) VOI calculation according to Dasmah et al.²⁹ (2012). Three schematic diagrams of different CT sections (axial and sagittal) are depicted, showing the maximum amount of bone in all dimensions. The crestal horizontal length (CHL), crestal horizontal width (CHW), and crestal vertical height (CVH) were measured. The mean value was calculated for each dimension, and the values were multiplied to obtain the VOI. (C) VOI calculation according to Hernández-Alfaro et al.²⁶ (2013). A plane was delineated using the posterior nasal spine and both infraorbital foramina as anatomical landmarks. The VOI was defined below this plane until the inferior limit of the residual alveolar ridge.

VOI, but no further details were mentioned³⁰.

Volumetric changes according to the surgical procedure performed

The autogenous iliac bone graft (IBG) was the most common donor graft for reconstruction of the edentulous maxilla (Tables 3 and 4). The bone graft surgery was performed under general anaesthesia or

local anaesthesia with or without intravenous sedation. Antibiotics used were penicillins (benzyl-, phenoxymethyl-, or aminopenicillin) or clindamycin (Tables 3 and 4).

Postoperative radiographic scans were performed during the first weeks. A second radiological follow-up was done on average between 4 and 6 months after the initial augmentation procedures before dental implantation (Tables 3 and 4).

Data on SIG procedures are reported in Table 3; five of the six studies reported volumetric data for SIG. Two of studies reported data on particulated autogenous bone grafts (PAG) of the iliac bone (IBG). One of these studies reported an average volume loss of 1.1 cm³ at 6 months postoperative, with a CV of -50%²⁸. The other study reported an average volume loss of 0.4 cm³ and CV of -25% at 4 months postoperative²⁰. Both studies described similar surgical techniques and methods of VOI calculation^{20,28}.

One study reported SIG procedures with PAG of autogenous IBG mixed with platelet-rich plasma (PRP). These procedures resulted in a VOI loss at 6 months postoperative of 1.5 cm³ at the test site and 2.0 cm³ at the control site. The reported CV were -33% and -42%, respectively²⁹.

PAG of autogenous ascending ramus grafts (ARG) showed an average volume loss of 0.5 cm³, or a CV of -24% at 6 months postoperative³⁰. The VOI loss after augmentation with an allogeneic distal femur head (DFH) graft was 0.7 cm³ in the first 6 months postoperative, with a CV of -30%³⁰.

Autogenous ARG mixed with demineralized bovine bone particles (DBBP) showed a VOI loss of 1 cm³ and a CV of -5% at 3-4 months postoperative²⁶.

Data concerning LBA procedures are described in Table 4. Only four of the six studies reported volumetric data on the LBA (Table 4). A monocorticocancellous bone block fixed with miniscrews (CCB-FMS) was used in all cases except in the test group in the study by Dasmah et al.²⁹. In that study, CCB-FMS ($n = 11$) was compared with a LBA technique consisting of a PAG mixed with PRP ($n = 11$).

Three studies reported data on the autogenous IBG fixed with a miniscrew as the monocorticocancellous bone block (CCB-FMS). One study reported an average volume loss of 1.1 cm³ and CV of -47% at 6 months postoperative²⁸, another an average volume loss of 0.4 cm³ and CV of -17% at 4 months postoperative²⁷, and the final one an average volume loss of 1.8 cm³ and CV of -37% at 6 months postoperative²⁹. All studies described similar surgical techniques and methods of VOI calculation²⁷⁻²⁹.

The LBA procedures in the clinical trial test group (Dasmah et al.²⁹), consisting of PAG of autogenous IBG mixed with PRP, resulted in a VOI loss of 3.2 cm³. The reported CV was -67% at 6 months postoperative²⁹. The resorption rate for LBA differed markedly between LBA of particulate bone mixed with PRP and LBA

Table 3. Surgical specifications—focus on sinus inlay grafts (SIG).

Sinus inlay graft (SIG) procedures	Population	Study	Surgical specifications	Interval radiographs	Changes in VOI	Coefficient of variation (CV)
Graft: autogenous IBG	Maxilla, $n = 10$	Johansson et al. (2001) ²⁸	General anaesthesia	No preoperative X-ray	V1 = 2.3 cm ³ (SD 0.8)	CV 6 months: −50%
Recipient: PAG	Sinus, $n = 20$		Incision: NM Antibiotics: yes (10 days) DFP: 4–6 weeks	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.2 cm ³ (SD 0.6)	
Graft: autogenous IBG	Maxilla, $n = 20$	Klijn et al. (2012) ²⁰	General anaesthesia	Preoperative X-ray	V1 = 1.7 cm ³ (SD NM)	CV 4 months: −25%
Recipient: PAG	Sinus, $n = 38$		Incision: crestal, full-thickness Antibiotics: yes (7 days) DFP: 3–4 weeks	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.3 cm ³ (SD NM)	
Graft: autogenous ARG	Maxilla, $n = 15$	Xavier et al. (2015) ³⁰ – Control site	Local anaesthesia	Preoperative	V1 = 2.0 cm ³ (SD 0.4)	CV 6 months: −24%
Recipient: PAG	Sinus, $n = 15$		Incision: crestal, full thickness, two vertical releasing incisions Antibiotics: yes (PE) DFP: NM	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.5 cm ³ (SD 0.5)	
Graft: allogenic DFH (FFB)	Maxilla, $n = 15$	Xavier et al. (2015) ³⁰ – Test site	Local anaesthesia	Preoperative	V1 = 2.5 cm ³ (SD 0.8)	CV 6 months: −30%
Recipient: PAG	Sinus, $n = 15$		Incision: crestal, full thickness, two vertical releasing incisions Antibiotics: yes (PE) DFP: NM	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.8 cm ³ (SD 0.6)	
Graft: autogenous IBG	Maxilla, $n = 11$	Dasmah et al. (2012) ²⁹ – Control site	General anaesthesia	No preoperative X-ray	V1 = 4.8 cm ³ (SD 1.8)	CV 6 months: −42%
Recipient: PAG mixed with PRP	Sinus, $n = 11$		Incision: NM Antibiotics: yes DFP: 1 month	Post-augmentation (V1) Pre-implantation (V2)	V2 = 2.8 cm ³ (SD 1.0)	
Graft: autogenous IBG	Maxilla, $n = 11$	Dasmah et al. (2012) ²⁹ – Test site	General anaesthesia	No preoperative X-ray	V1 = 4.5 cm ³ (SD 1.9)	CV 6 months: −33%
Recipient: PAG mixed with PRP	Sinus, $n = 11$		Incision: NM Antibiotics: yes DFP: 1 month	Post-augmentation (V1) Pre-implantation (V2)	V2 = 3.0 cm ³ (SD 1.7)	
Graft: autogenous ARG and DBBP	Maxilla, $n = 14$	Hernández-Alfaro et al. (2013) ²⁶	IV sedation and general anaesthesia	Preoperative	V0 = 11.3 cm ³ (SD 2.3)	CV 4 months: −5%
Recipient: PAG mixed with DBBP	Sinus, $n = 28$		Incision: crestal, full-thickness Antibiotics: yes (7 days) DFP: 1 week	Post-augmentation (V1) Pre-implantation (V2)	V1 = 20.0 cm ³ (SD 2.9) V2 = 19.0 cm ³ (SD 2.4)	

ARG, ascending ramus graft; DBBP, demineralized bovine bone particles (Bio-Oss); DFH, distal femur head; DFP, denture-free period; FFB, fresh frozen bone; IBG, iliac bone graft; IV, intravenous; NM, not mentioned; PAG, particulated autogenous graft; PE, preoperative; PRP, platelet-enriched plasma; SD, standard deviation; VOI, volume of interest.

Table 4. Surgical specifications—focus on lateral bone augmentation (LBA).

Lateral bone augmentation (LBA) procedures	Population	Study	Surgical specifications	Interval radiographs	Changes in VOI	Coefficient of variation (CV)
Graft: autogenous IBG	Maxilla, $n = 10$	Johansson et al. (2001) ²⁸	General anaesthesia	No preoperative X-ray	V1 = 2.3 cm ³ (SD 1.2)	CV 6 months: −47%
Recipient: CCB-FMS	Sinus, $n = 20$		Incision: NM Antibiotics: yes (10 days) DFP: 4–6 weeks	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.2 cm ³ (SD 0.8)	
Graft: autogenous IBG	Maxilla, $n = 16$	Dreiseidler et al. (2016) ²⁷	General anaesthesia	No preoperative X-ray	V1 = 2.5 cm ³ (SD 1.3)	CV 4 months: −17%
Recipient: CCB-FMS			Incision: high in vestibular gingiva Antibiotics: yes DFP: NM	Post-augmentation (V1) Pre-implantation (V2)	V2 = 2.1 cm ³ (SD 1.2)	
Graft: autogenous IBG	Maxilla, $n = 11$	Dasmah et al. (2012) ²⁹ – Control site	General anaesthesia	No preoperative X-ray	V1 = 4.8 cm ³ (SD 1.0)	CV 6 months: −37%
Recipient: CCB-FMS	Control, $n = 11$		Incision: NM Antibiotics: yes DFP: 1 month	Post-augmentation (V1) Pre-implantation (V2)	V2 = 3.0 cm ³ (SD 1.5)	
Graft: autogenous IBG	Maxilla, $n = 11$	Dasmah et al. (2012) ²⁹ – Test site	General anaesthesia	No preoperative X-ray	V1 = 4.8 cm ³ (SD 1.5)	CV 6 months: −67%
Recipient: PAG mixed with PRP	Test, $n = 11$		Incision: NM Antibiotics: yes DFP: 1 month	Post-augmentation (V1) Pre-implantation (V2)	V2 = 1.6 cm ³ (SD 0.6)	
Graft: autogenous ARG and DBBP	Maxilla, $n = 14$	Hernández-Alfaro et al. (2013) ²⁶	IV sedation and general anaesthesia	Preoperative	V0 = 11.3 cm ³ (SD 2.3)	CV 4 months: −5%
Recipient: CCB-FMS, DBBP, RCM	Sinus, $n = 28$		Incision: crestal, full-thickness Antibiotics: yes (7 days) DFP: 1 week	Post-augmentation (V1) Pre-implantation (V2)	V1 = 20.0 cm ³ (SD 2.9) V2 = 19.0 cm ³ (SD 2.4)	

ARG, ascending ramus graft; CCB-FMS, monocorticocancellous bone block fixed with miniscrews; DBBP, demineralized bovine bone particles (Bio-Oss); DFP, denture-free period; IBG, iliac bone graft; IV, intravenous; NM, not mentioned; PAG, particulated autogenous graft; PRP, platelet-enriched plasma; RCM, resorbable collagen membrane (Bio-Gide); SD, standard deviation; VOI, volume of interest.

with a monocorticocancellous iliac bone graft at 6 months postoperative²⁹.

The use of an autogenous ARG bone block added with xenografts (DBBP covered with a resorbable collagen membrane) showed a VOI loss of 1 cm³ and a CV of -5% at 3–4 months postoperative²⁶.

For the comparison of SIG with LBA procedures, two studies provided useful data^{28,29}. In the first study, the rate of volume loss did not differ much between SIG and LBA (-50% vs -47%)²⁸. In the second study, volume loss at the SIG sites (with CV -33% and -42%) differed from that at the LBA sites (CV of -37% for CCB-FMS and -67% for PAG mixed with PRP)²⁹.

Discussion

Population specifications

Over the decades, increasing evidence has suggested that the causative pathology differs between partially edentulous patients and those who are completely edentulous (caries, trauma versus periodontal diseases as the cause of dental loss)^{18,31,32}. Also, occlusal stability and/or dental support is an important difference when considering pressure forces on different bone augmentation techniques between partially and completely edentulous patients. Therefore, the decision was made to include only study populations with a completely edentulous atrophic maxilla.

Although a limited number of articles met the inclusion criteria, the mean age of the study population and the initial dimensions of the alveolar ridge (CHW and CVH) were comparable throughout. The predominance of female patients in the study populations was notable. A shortcoming of all of the included articles was the small size of the study populations, which makes detecting differences among them difficult.

Radiological volumetric analysis

The use of CBCT has offered enormous advantages in dose reduction, availability, and costs, leading to rapid and clear individual data acquisition. The main disadvantage of CBCT is the absence of Hounsfield units, which makes it difficult to compare images in a validated way³³. Due to recent changes and dose reductions in the field of CT scans, micro-CT might represent a future alternative. It appears that no validation study has compared the different methods of VOI calculation, a

statement confirmed by most authors of the included studies^{26–28}.

Overall, the methods described provided a clear description of how to calculate the VOI. The method used by Dasmah et al. (Fig. 3B) is effective for comparing two surgical protocols in the same patient, but seemed to overestimate the real volume of bone compared with the other studies²⁹. By taking the mean of the largest CVH, CHW, and CHL, a volumetric rectangle is measured; in reality, the bone graft has a more elliptic shape, so the volume of the real augmented volume block is overestimated in comparison with the data reported in the other studies. Hernández-Alfaro et al. evaluated treatment outcomes with volume-rendering software tools for CBCT, allowing a standardized three-dimensional analysis of the results (Fig. 3C)²⁶. It should be mentioned that by making a two-dimensional plane through the infra-orbital foramen and posterior nasal spine, the zygomas are partially considered in calculations of the VOI. The method described seems to be one of the quickest means of obtaining preoperative and postoperative volumetric data. The study by Hernández-Alfaro et al. was the only one to provide preoperative volumetric data.

Volumetric changes according to the surgical procedure performed

No studies that met the inclusion criteria reporting data on vertical augmentation procedures or interpositional grafts were found. The preferred procedures were SIG and LBA. The distinction between these techniques was made for comparability of the results. Otherwise, both procedures are difficult to separate in the restoration of an edentulous maxilla, and should be seen surgically as one entity.

The preferred donor sites were the anterior iliac crest (IBG) and the mandibular ascending ramus (ARG) (Tables 3 and 4). No published studies with a completely edentulous population reporting volumetric data on calvarial or chin bone grafts were found. The latter is possibly explained by a discrepancy in the amount of graft volume necessary and the amount available to harvest in the interforaminal area. Some authors preferred allografts, which have the advantage that no donor site is necessary³⁰. Nevertheless, allografts have been plagued by their unpredictable rates of resorption, bone formation, and infection rate²².

A denture-free period (1–4 weeks) ensured good healing of the mucoperiosteal flap. This healing prevented wound dehiscence and interference from wound irritation or friction, reducing micromovements of the bone grafts.

One research group used collagen barrier membranes²⁶. Based on the present data (mainly due to the different method of calculation of the VOI), it is difficult to draw firm conclusions on the use of membranes. Gielkens et al. concluded that the added value of these membranes in preventing bone resorption in the completely edentulous maxilla is still debatable. The potential benefits of using either resorbable or non-resorbable barrier membranes do not overcome the risk of exposure during the healing period and subsequent complications³⁴.

With regard to the SIG procedures (Table 3), data for the studies using autogenous IBG showed that the volume loss in the study by Klijn et al.²⁰ was half the volume loss reported by Johansson et al.²⁸ (CV -25% vs -50%). Both studies used the same technical and surgical methods, except the time to dental implantation. The discrepant results reported by Klijn et al. could be explained by the smaller augmented bone volume used, or the fact that the study population was edentulous for more than 10 years, making additional post-extraction resorption of the alveolar process less acceptable²⁰.

Another study (Dasmah et al.²⁹), with a different technical method, also reported volumetric data on SIG with autogenous IBG. The raw volume data were not comparable to those of the former studies, but the CV values were located in between (-33% and -42%).

The volumetric data of SIG with ARG or allogeneic DFH were comparable to those of the previously mentioned studies, and no major differences in the CV values were noted between the allografts and autografts³⁰.

The lack of baseline CBCT or CT scans makes it difficult to compare the initial situations between the aforementioned authors. Uchida et al. (1998), in a study involving a group of partially edentulous patients, reported that the inferior portions of the sinus measured on CT images were 0. cm³ for 5-mm lifting and 1.9 cm³ for 10-mm sinus floor elevation³⁵, which corresponds with the data reported above. Based on the present data, it seems that no type of graft can be preferred over another with regard to volumetric osseous changes over time.

Data on LBA procedures (Table 4) showed that an autogenous monocorticocancellous bone block was fixed with a miniscrew to the maxilla in three studies. The resorption rate or CV varied from

−17%²⁷ to −37%²⁹ and −47%²⁸. The vestibular incision in the mobile mucosa used by Dreiseidler et al. may result in less wound tension, leading to fewer infectious complications²⁷. This incision could explain the lower resorption rate of the grafted volume in comparison to the other studies^{27–29}.

LBA reconstruction with particulated IBG mixed with PRP showed significantly more resorption in comparison to CCB-FMS²⁹. Autologous bone blocks still appear to be the most reliable and secure procedure for LBA in the case of extreme resorption³⁶.

The autogenous ARG bone block added with xenografts (DBBP) and covered with a resorbable collagen membrane showed a mean augmentation of 9 cm³ in LBA and SIG procedures, and a CV of −5%²⁶. The autogenous ramus graft could represent an alternative intraoral donor site, with less morbidity than with anterior iliac grafts²⁶. By adding the volume of the zygomas in the VOI calculation, the actual resorption was underestimated compared to the other methods, because the initial volume was relatively larger. Other authors have also suggested that the envelopment of the autogenous grafts with DBBP could reduce resorption of the autograft³⁷.

When comparing SIG with LBA procedures, it has been postulated that the reconstruction with an onlay graft (LBA) is more prone to resorption than the reconstruction with an inlay graft (SIG); this was the case for the test site in the study by Dasmah et al.^{22,29,38}. Otherwise, resorption does not seem to vary much between autogenous IBG CCB-FMS as LBA and PAG of IBG for SIG.

General considerations

When moving forward with bone grafting procedures, several physiological, structural, and morphogenetic factors have to be considered²². Physiologically, the healing of an autogenous bone graft parallels that of fracture repair. Structurally, graft survival is maximized when the orientation of the cancellous surface of the graft abuts the fresh edges of the host bone and the periosteal surface is in contact with the soft tissues. The position of a bone graft (i.e., inlay or onlay graft) has additional effects on revascularization (three-wall defect vs. one-wall defect). Increased contact results in more rapid and complete revascularization. The use of rigid fixation in bone grafting promotes the ingrowth of blood vessels. The embryological origin of a graft, the subject of much debate, is significant only in that it determines the

relative proportions of cortical and cancellous bone within the graft. The microarchitecture of a bone graft is perhaps the most important determinant of graft volume maintenance³⁹. The characteristics of the soft tissue envelope at the recipient site and the position in which the graft is placed (i.e., inlay vs. onlay) dictate the mechanical forces on the grafted bone. In essence, the form of a bone follows its function (Wolff's law). Morphogenetically, many different types of bone substitute can be used to supply the material needed for the procedure, e.g., autologous, allogeneic grafts, xenograft, or alloplastic materials.

Alveolar bone resorption occurs after tooth extraction, and in all of the included studies, bone grafting procedures were also prone to resorption. The concept of the biological tissue envelope states that the bone form follows function^{40,41}. Consequently, if the bone is not functional, it will resorb, or if bone is too extensively present, the functionality (e.g., by dental implants) in its environment will return it to its original dimensions.

The primary goal of a bone grafting procedure is to create a stable bony base to facilitate the surgical placement of dental implants. Grafting solutions can provide a less prosthetically demanding scenario because the alveolar anatomy is restored. This systematic review describes multiple surgical ways to achieve this goal.

A few interesting observations were made concerning volumetric osseous changes after bone augmentation procedures in the completely edentulous atrophic maxilla: (1) the lack of universally accepted success criteria and validated volume calculation tools remains a significant obstacle in comparing the different studies and surgical techniques. (2) In the case of the sinus inlay grafts (SIG), the type of graft does not seem to affect the volumetric osseous changes before dental implantation. (3) In the case of lateral bone augmentation (LBA), corticocancellous bone block fixed with miniscrews (CCB-FMS) proved to be more stable over time than particulated autogenous grafts (PAG). A non-crestal incision providing less bone volume resorption seems to be an interesting area for further investigation.

Many surgical techniques have been developed to restore the dimensions of the alveolar process in the edentulous maxilla, and all of them are prone to resorption. Although patients with an edentulous maxilla seem to be a well-defined study population, some interesting

trends are noted but no firm evidence exists to favour one augmentation procedure over the other, due to different radiological analyses.

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Competing interests

No conflict of interest to declare.

Ethical approval

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Patient consent

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Appendix A. Supplementary data

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