Systematic Review

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Comparative Effectiveness of Vertical Ridge Augmentation Techniques for Dental Implant Treatment: A Systematic Review

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Abstract

Background: Dental implants placement in long-standing edentulous areas often encounter the problem of alveolar height deficiency from gradual bone resorption over time. Therefore, vertical bone augmentation prior to implant placement would be much needed.

Objectives: To compare the effectiveness of various vertical ridge augmentation techniques.

Methods: This review followed the PRISMA guideline. Electronic and manual searches of randomized controlled trials (RCTs) were conducted through the MEDLINE, CENTRAL, Embase, and Scopus databases. The primary outcome was vertical bone gain. Secondary outcomes were bone resorption, complications, implant survival, and success rates. The Cochrane risk-of-bias assessment tool version 2 was used for quality assessment.

Results: Data analyses of the 29 included studies indicated that distraction osteogenesis (DO) provided the highest final vertical bone gain (8.38±1.74 mm.) followed by inlay bone grafting (2.69±0.37 to 7.00±1.76 mm) and guided bone regeneration (GBR) (1.50±1.60 to 6.86±0.94 mm). The highest degree of bone resorption was observed with onlay bone grafting (0.60±0.70 to 4.77±1.67 mm). The DO and GBR techniques demonstrated 20-60% and 0-47% complication rates, respectively. Implant survival and success rates for all ridge augmentation techniques were over 90% and 60%, respectively.

Conclusions: From this study, all vertical bone augmentation techniques can effectively increase the alveolar ridge height. While DO provides the greatest vertical bone gain, the GBR techniques might be a more clinically practical option. However, future well-planned RCTs to identify effective vertical bone augmentation techniques are still warranted.

Keywords: distraction osteogenesis, guided bone regeneration, inlay graft, onlay graft, systematic review

Introduction

Tooth loss is one of the problems that negatively impacts the patients' oral health-related quality of life by lowering self-confidence and impairing the biting or chewing functions, which may consequently weaken the patients' overall health.[1,2] To date, dental implant treatment has been increasingly selected from its reliable outcome and long-term success. The dimensions of alveolar ridge would normally be maintained by the presence of healthy and functional teeth. However, when there is tooth loss, bone resorption and subsequent loss of the alveolar ridge dimensions could occur, which, over time could result in anatomical limitations for dental implant placement.[3,4]

Vertical alveolar ridge augmentation techniques are considered sensitive procedures due to the frequent complications associated with them. However, the success of vertical bone augmentation is influenced by many factors, including variability in clinical settings and operator experience.[4] The main surgical procedures for increasing vertical bone height included distraction osteogenesis (DO), inlay bone graft, onlay bone graft, and guided bone regeneration (GBR).[5,6] DO is a technique involving the gradual, controlled separation of surgically created bone fragments, which induces new bone formation within the gap.[7] Inlay bone graft is a procedure that the bone grafting material is placed between bone segments at the recipient site. Onlay bone graft is a technique that places bone grafting material on the alveolar bone defect, and fixed with either screw, plate, or implant. Guided bone regeneration is a technique that fills the defective bone area with bone grafting material and covers with barrier membrane.[6,8] Ongoing researches are being conducted to develop proper vertical ridge augmentation methods, that are simple, and could provide predictable outcomes, with less complications. Besides exploring different vertical bone augmentation techniques, the use of autogenous bone graft, bone substitutes, and diverse types and forms of barrier membranes are also being investigated. However, the efficiencies of the reported methods still varied among different studies.[8,9]

This study aims to compare the effectiveness of various vertical ridge augmentation techniques, by evaluating vertical bone gain, resorption levels of the alveolar ridge after complete healing, the occurrence of postoperative complications, the survival and success rates of dental implants placed in those areas.

Materials and Methods

Protocol development and research question

This systematic review used the updated PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) as the reporting guideline.[10] The study protocol was developed and registered with the International Prospective Register of Systematic Reviews (PROSPERO), with the registration number of CRD42024508826. The research question was "In patients with vertical alveolar ridge deficiency, what is the effectiveness of various vertical ridge augmentation techniques on vertical bone gain?" It could be written in PICO format, as follows: participant (P), patients with vertical alveolar ridge deficiency; intervention (I), any ridge augmentation techniques used as intervention; comparator (C), any ridge augmentation techniques used as control; and outcome (O), vertical bone gain as the primary outcome while the resorption level after complete healing, postoperative complications, the survival and success rates of implants placed at the augmentation sites were considered as secondary outcomes. In this study, only the randomized clinical controlled trials (RCTs) were included for the review.

Search strategy

An electronic search for relevant studies was performed in MEDLINE, EMBASE, Scopus, and CENTRAL databases from their inception date to August 22, 2025. The search strategy included only terms or keywords related to the review question, and only studies published in English language were recruited. The authors also reviewed the reference lists from previously published systematic review and/or meta-analysis on the same topic. All eligible studies from electronic databases and the reference lists will be included at this stage.

The following combination of keywords were used as search strategies which were adapted to each database: (((alveolar ridge OR alveolar bone OR alveolar crest) AND (defect* OR deficien* OR loss* OR atroph*)) OR ((Alveolar Ridge OR Alveolar bone OR Alveolar crest) AND (gain* OR augment*)) OR (Bone graft* OR Bone substitut* OR Alveolar graft*)) AND ((block graft* OR onlay graft*) OR (alveolar OR distraction osteogenes*) OR (guided bone regeneration* OR (particulat* AND graft*)) OR (sandwich* AND techni*) OR (tent* OR pole* OR screw*)) AND (((Bone OR alveolar OR alveolar bone) AND (gain* OR height*))).

Inclusion criteria

1. Randomized controlled clinical trials in which participants were patients with vertical alveolar ridge deficiency who needed dental implant treatment.
2. Intervention treatments with DO, inlay bone graft, onlay bone graft, or guided bone regeneration
3. Comparator treatment with DO, inlay bone graft, onlay bone graft, or guided bone regeneration
4. Outcome showed vertical bone gain

Exclusion criteria

1. Case report, case series, clinical controlled trial, systematic review, or meta-analysis.
2. Vertical bone augmentation at posterior maxilla with osteotome sinus floor elevation or lateral window approach
3. Vertical bone evaluation after socket preservation

Literature screening and data extraction

Relevant studies retrieved from the databases and the manual search were imported to the Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia (available at www.covidence.org), where the duplicates were removed. The remaining studies were screened through their titles and abstracts by 2 reviewers (C.K. and P.T.) and selected according to the inclusion and exclusion criteria. Full text articles of potentially eligible studies were retrieved and independently assessed by the two reviewers (C.K. and P.T.). When disagreements or uncertainties regarding the eligibility of a study occurred, they were resolved by discussions with a third reviewer (M.S.). Reasons for the exclusion of any study were recorded.

The authors used a prepared form to record the required data from the included studies. Data extraction was done by the two reviewers (C.K. and P.T.), who independently read the full-text articles of the studies included. If there is any disagreement, the third reviewer (M.S.) will be consulted. The extracted data included the following: first author's name, publication year, mean age ± standard deviation (or median age and range), gender, type of study design, sample size (classified by number of surgical sites and implants), surgical technique defined as intervention, surgical technique defined as control, bone grafting materials, source of bone graft, barrier membranes, special procedures (such as simultaneous implant placement, using tenting screw), follow-up time (healing period), primary outcome (vertical bone gain), secondary outcomes (bone resorption, complications, implant survival and success rate), measurement methods, statistical value, and information for assessment of the risk of bias.

Qualitative assessment (risk of bias)

The quality of the included RCTs, or risk of bias, was independently assessed by 2 reviewers (C.K. and P.T.) and any disagreement will be resolved by discussing with the third reviewer (M.S.). The Cochrane risk-of-bias assessment tool version 2 (RoB 2) was used for quality assessment of each randomized controlled trial.[(11)] The tools evaluated five aspects as follows: randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. Each randomized controlled study was rated as low risk, some concerns, or high risk of bias. The RoB 2 assessment of all included studies will be visualized using robvis, a tool that generates risk-of-bias plots.[(12)]

Outcome parameters

This study collected vertical bone gain (mm) at complete healing period as the primary outcome. If the included studies reported the level of bone resorption, the presence of postoperative complications, or the implant survival or success rates, these outcomes were recorded as secondary outcomes. Vertical bone gain and bone resorption were compared according to types of surgical techniques.

Results

Initial literature search via electronic databases and the manual search revealed 5,000 relevant studies which were retrieved as follows: 1,772 studies from CENTRAL, 1,081 studies from PubMed, 1,148 studies from Embase, 999 studies from Scopus, and 43 studies from the manual search. After removal of 1,613 duplicate studies, 3,430 studies were screened from their titles and abstracts which resulted in exclusion of 3,356 studies. The full-text articles of the 74 relevant studies were retrieved, and extensively assessed for their eligibility, mainly in their Material and Methods and Results sections. Consequently, 45 studies were excluded with the reasons shown in Figure 1, and finally 29 RCT studies were eligible to be included in this review. The extracted data of baseline characteristics (augmentation technique, bone grafting material, source of bone, type of membrane, special procedure) of the included studies[13-41], were shown in Table 1. Vertical bone gain and bone resorption according to the types of surgical techniques were shown in Tables 2-5. The complications, implant survival and success rates from the included studies were summarized in Table 6.

Risk of bias assessment

Qualitative assessment of the included studies was performed by using RoB 2 tool, which categorized the studies as having low (1 study), some concerns (16 studies) and high (12 studies) risk of bias as shown in Figure 2. The overall risk of bias, in percentages, were depicted as low in 3.45%, some concern in 55.17%, and high in 41.38% of the studies included (Figure 3).

Data analysis

All included studies compared either two or three surgical techniques in each study. The surgical techniques of vertical bone augmentations studied include distraction osteogenesis (DO), the inlay or onlay bone graft, and the guided bone regeneration (GBR) techniques. From the 29 included studies, there were 3 studies of DO, 8 studies of onlay (bone block) graft, 7 studies of inlay bone graft (sandwich technique), and 19 studies of GBR technique. The details of the surgical techniques, their group assignments, bone grafting materials, membranes use, and any additional procedures performed in each study were shown in Table 1.

From the 3 studies that used DO to increase alveolar bone height, the vertical bone gain, at completion of distraction period, ranged from 5.33±1.58 mm to 10.36±2.96 mm. However, only one study showed final vertical bone gain of 8.38±1.74 mm after 3 to 4 months of healing period (Table 2). By using the inlay bone grafting technique,

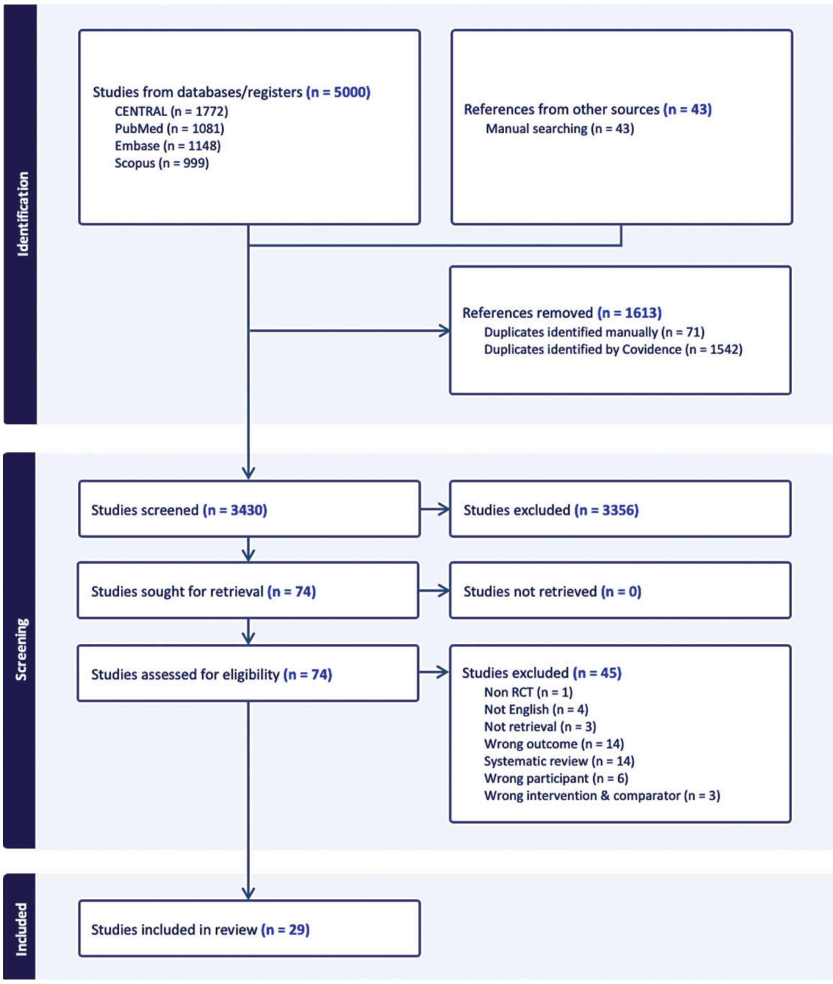

Figure 1: PRISMA flow diagram of included studies.

immediate vertical bone gain ranged from 5.10±1.10 mm to 6.20±2.20 mm. This technique showed final vertical bone gain from 2.69±0.37 mm to 7.00±1.76 mm after the healing period of 3 to 6 months (Table 3). With the onlay bone grafting technique, immediate vertical bone gain ranged from 2.90±0.90 mm to 6.52±1.11 mm, while the final bone gains were from -0.02±1.86 mm to 4.80±1.50 mm, which demonstrated bone height decrease overtime. Interestingly, El Zhawy and colleagues[23] reported the highest level of bone graft resorption at 4.77±1.67 mm, (Table 4).

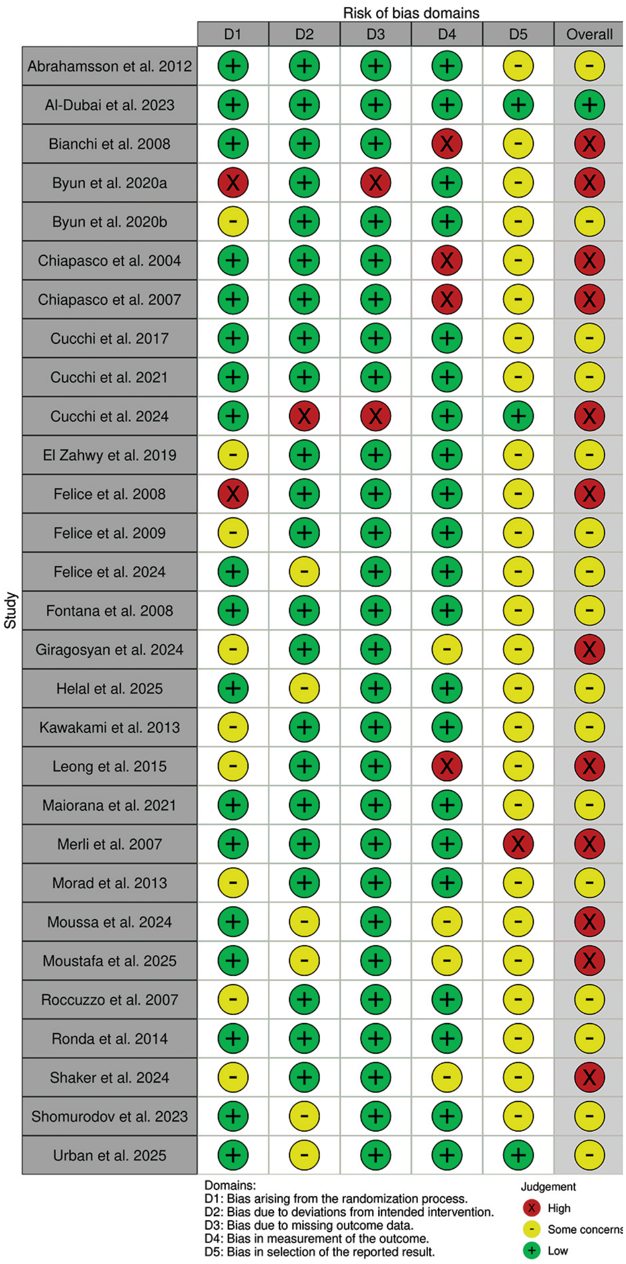

Figure 2: Risk of bias of each study.

The GBR technique showed immediate vertical bone gain ranged from 2.73±0.79 mm to 6.37±0.71 mm, and final vertical bone gain ranged from 1.50±1.60 mm to 6.86±0.94 mm (Table 5). From the GBR studies, most of them demonstrated some degree of bone resorption at the complete healing period, which then resulted in the lower level of final vertical bone gain (VBG) when compared with the immediate post-op VBG. However, some studies showed no bone resorption at the complete healing period, which led to a somewhat higher final VBG relative to the immediate post-op VBG. These outcomes may be influenced by the differences in the GBR techniques used in those studies.

Data extraction of the complications, implant survival, and success rates from the vertical augmentation techniques, from all the included studies were shown in Table 6. The complications associated with the DO technique mainly included lingual inclination of the distracted bone, incomplete distraction, and infection. Whereas wound dehiscence, infection, neurosensory disturbance, and graft loss were the complications observed from the other techniques. Complication rates varied substantially by technique: DO ranged from 20% to 60%, while the ranges for inlay bone graft, onlay bone graft, and GBR were 0% to 100%, 0% to 88.89%, and 0% to 46.67%, respectively (Table 7). Survival and success rates of the implants placed in the vertically augmented bone were reported in 17.24% (5 out of 29 studies) and 13.79% (4 out of 29 studies) of the included studies, respectively. Implant placements after DO, inlay, and onlay grafting techniques had 100% implant survival rate. However, one study reported 94% to 97% of implant survival rates from the GBR technique. The success rate, at one year, of implants placed in the bone which had undergone DO ranged from 93.7% to 100%. From the inlay technique, the implant success rates were shown to be at 95.2% (at 1 year) and went down to 90% (at 17 to 22 months). Implants placed following onlay bone augmentation demonstrated success rates ranging from 86.9% to 89.5% (at 1 to 2 years). For GBR technique, there was one included study demonstrated success and survival rates.(18) The survival rate of GBR was 100%. The success rate of GBR technique with simultaneous implant placement was 61.5% at 2 to 3 years, while GBR technique alone was 75% at 2 to 3 years.

The summary of outcomes for each vertical bone augmentation technique was presented in Table 7. DO

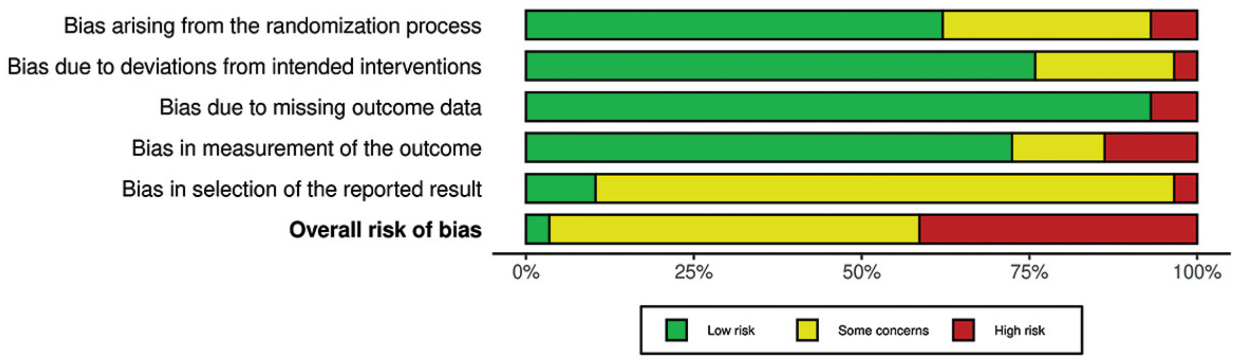

Figure 3: Risk of bias domains in percentage.

provided the most final vertical bone gain, while onlay bone graft resulted in the lowest. In terms of bone resorption, onlay bone graft also demonstrated the highest range, while inlay bone graft showed the lowest. The highest range of complication rate was associated with inlay bone graft, while GBR showed the lowest range. Although implant survival rates were generally high across all techniques, implant success rates showed notable variability, ranging from 61.5% to 94.7% depending on the specific technique and follow-up duration.

Discussions

The objective of the study was to compare the effectiveness of various surgical vertical augmentation techniques by looking at the outcomes of vertical bone gain, resorption of the alveolar ridge after bone remodeling, complications from the treatments, as well as the success and survival rates of implants placed in the areas where the alveolar ridge height has been surgically increased.

Distraction osteogenesis

Distraction osteogenesis resulted in the highest final vertical bone gain (8.38±1.74 mm) compared to the other techniques, despite the occurrence of some bone resorption during the healing process. From the review of our included studies, final vertical bone gain from the DO technique was comparable to that reported in other non-RCT studies. Marianetti and colleagues[42] reported mean vertical bone gain after distraction osteogenesis of 10.5 mm (range 7-17 mm). Sezer and colleagues[43] reported mean vertical bone gain of 7.2±0.8 mm. Mohanty and colleagues[44] claimed that their results of vertical bone gains ranged from 6 to 11 mm. Distraction osteogenesis seem to provide large amount of bone gain. Most likely, it could be that the distracted bones are autogenous bones, and they are attached to soft tissues which provide sufficient blood supply to the bone segment. At the same time, during the distraction phase, new soft tissue is created along the tension direction from the distraction device (distraction histogenesis) and receives blood supply from the new bone formation process between the bone segment and the bone base.[45] Although DO showed good results in vertical bone gain, bone resorption still occurred. Mean bone resorption of the included studies ranged from 0.3±0.3 to 1.98±1.34 mm. The results were in accordance with previous retrospective studies.[46,47] Reininger and colleagues[46] has shown that average bone resorption was 1.4±0.5 mm, and the rate of resorption ranged from 7% to 25%. From the study of Ettl and colleagues[47], it was shown that mean bone resorption was 1.8 mm with the resorption rate of 21.1%. From the reported rates of resorption, overcorrection of the distraction length at least 20% would be recommended. Complications can be found at all stages of the procedure. From our review, lingual inclination of the distracted segments was observed in all the 3 DO RCT studies, with some reports of infection and incomplete distraction.[15,18,19] Previous studies have reported other complications from the DO technique such as basal bone fracture, inadequate vestibular depth after complete distraction, and device failure.[47-51] As for the success rates of dental implants placed in the vertically increased bone height by DO technique, the 3 included RCTs demonstrated 94.1% to 94.7% success, at 2 to 3 years, which was lower than the reported 100% success rate from the retrospective study of Sezer and colleagues.[43] However, since the number of RCTs for vertical bone augmentation by DO is still low, it might be difficult to conclude the implant success rate in distracted alveolar bone.

Inlay technique

The inlay bone grafting or sandwich technique demonstrated high amounts of final vertical bone gain in the included studies, with the highest bone gain of 7.00±1.76 mm (Table 3). Bone resorption from the inlay technique ranged from 0.60±0.40 mm to 1.65±0.94 mm, which was relatively lower than those from the other vertical augmentation techniques. The bone resorption level was comparable to that from the previous meta-analysis study which showed bone resorption ranging from 0.50 to 2.3 mm.[52] The main benefit of the inlay technique is that blood supply to the osteotomized segments could be maintained[53], which could be a possible reason for the lesser bone resorption when compared to other techniques. Moreover, the types of bone grafting materials used e.g. bone block, or particulate bone may influence the healing potential within the inlay grafting area. The particulate bone could be more closely adapted to the recipient site when compared to the bone block, therefore, grafting with the mix of bone substitutes could be beneficial for the bone regeneration in the grafting area.[54] From the reviewed studies, the most reported complication associated with the inlay bone grafting technique was temporary neurosensory disturbance of inferior alveolar nerve, which is in agreement with previous studies.[55-59] In addition, wound dehiscence and fracture of bone fragment have been reported in the included studies, which were consistently shown in previous studies.[60-65] The implant survival rates of included studies were 100% and the success rates were 95.2% (at 1 year) and 90% (at 17 to 22 years) (Table 6). The results were comparable to the previous meta-analysis study which reported the survival rate ranging from 92% to 100% and the success rate ranging from 87.2% to 96.8%.[52]

Onlay technique

By using the onlay bone grafting technique, final vertical bone gain from the included studies ranged from -0.02±1.86 mm to 4.80±1.50 mm. However, this bone grafting technique showed higher degrees of bone resorption (0.60±0.70 mm to 4.77±1.67 mm) (Table 4) when compared to the other bone grafting techniques. In the 8 included studies, the edentulous ridges were vertically augmented with autogenous bone blocks, the remaining gaps were filled with particulate bone autograft and the block grafts were fixed with titanium screws in 7 studies or dental implants in 1 study. From these studies, it is apparent that onlay bone grafting with simultaneous implant placement for fixation resulted in high degree of bone resorption than the bone blocks fixed with titanium screws. The staged onlay graft could provide sufficient vertical bone volume before implant placement, then primary stability of implant could be achieved.[66] The primary challenge with the onlay bone augmentation technique is soft tissue management to ensure complete wound closure. Due to high resorption rate during the first year, the grafts should be harvested in larger sizes to account for volume loss during the initial resorption phase.[8] The complications associated with onlay bone grafting consisted of wound dehiscence, graft loss, graft mobility, paresthesia, infection, and crack of bone block. Only 2 of the studies reported the implant survival rate of 100%, while the implant success rates were lower than 90%. The implant survival and success rates from our study were consistent to a previous systematic review which reported implant survival rate ranged from 72.8% to 100%, and implant success rate ranged from 86.9% to 100%.[8]

Guided bone regeneration

The GBR technique was the preferred technique for vertical bone augmentation as seen from the largest number of treatment arms in all included studies. It is a versatile procedure which could be adapted and modified in many alveolar bone grafting conditions. The GBR techniques may vary in terms of surgical process, the types of bone substitutes, types of membrane used, and with or without simultaneous implant placement. However, there were complications from this procedure especially wound dehiscence.[67,68]

The use of GBR technique resulted in final vertical bone gain ranging from 1.50±1.60 mm to 6.86±0.94 mm (Table 5). The large gap between the lower and upper range of bone gains might be due to the use of varying surgical techniques, bone grafting materials and barrier membranes in each study. Bone resorption at the complete healing period ranged from -0.81±0.74 mm to 2.32±1.09 mm. Interestingly, negative values of bone resorption were shown in 3 studies(20,32,38), which represented some bone gain rather than resorption. These negative values of bone resorption were presented in the studies that used GBR techniques with simultaneous implant placement and therefore resulted in the higher final bone gain when compared to the immediate post-operative vertical bone gain. This might be the result of a process where, after implant placement and the addition of bone grafting materials, the barrier membranes were adapted to cover above the shoulder of the implants. The barrier membranes used in these three studies(20,32,38) were non-resorbable membranes (PTFE or titanium mesh), which might create a space-maintaining effect allowing for more bone growth.(69) In addition, the bone grafting materials used in these studies were either combinations of autograft and allograft or xenograft, which promote bone growth with the biological mechanisms of osteogenesis, osteoinduction and osteoconduction.(70) However, other studies that used non-resorbable membranes and the combinations of bone grafting materials did not provide the same results. The frequently occurred complications associated with GBR techniques included wound dehiscence, paresthesia, infection, and membrane exposure. The implant survival rates were higher than 90%. The implant success rates following one year in the group using GBR technique were higher than 80%. However, they ranged from 61.5% (at 2 to 3 years) to 75% (at 2 to 3 years). The lowest success rate (61.5%) was noticeable in the study of Chiapasco and colleagues(18), that utilized the GBR technique with simultaneous implant placement.

From all vertical ridge augmentation techniques reviewed in this study, DO yielded the greatest final vertical bone gain, followed by inlay bone grafting, GBR, and onlay bone grafting. Regarding bone resorption and complications, onlay bone grafting demonstrated the highest degree of bone resorption. Inlay bone grafting had the highest complication rate, whereas GBR showed the lowest complication rate. Despite the limited number of studies that reported on implant survival and success rates, all vertical augmentation techniques demonstrated high implant survival rates. However, implant success rates were notably different in two augmentation techniques i.e. highest implant success rate was achieved with DO, while the lowest success rate was shown in the GBR technique. It is important to note that these reported success rates were assessed at varying follow-up periods (Table 7).

Limitation

This study is a systematic review which aims to collect and analyze only randomized clinical controlled studies. However, the number of randomized clinical controlled studies of vertical ridge augmentation was rather minimal and varied in terms of the parameter studied which, in turn, affected the data gathering of each surgical technique, number of participants, and lack of secondary outcomes in some studies. In addition, the restriction of included studies to only English-language publications is another limitation of this study. Moreover, the clinical heterogeneity between the studies was high; as a result, it was not suitable for performing the meta-analysis. Therefore, future studies should be properly designed and conducted.

Table 1: Characteristics of included studies.

Author (year)	Type of RCT	Mean age ± SD or median age (Min to Max) (years)	Male/ female	Treatment arm	Technique	Bone grafting material	Source of bone	Membrane	Special procedure	*p* value between groups of final VBG
Abrahamsson *et al.* 2012[13]	Parallel	20 (18 to 49)	6/4	Control	Onlay	Block autograft	Lateral border of mandible using Piezosurgery	Not used	Titanium screw fixation	N/A
		22 (18 to 55)	8/2	Test	GBR	Particulate autograft	Lateral border of mandible using bone scraper	Titanium mesh, collagen membrane	Soft tissue expansion before GBR	
Al-Dubai *et al.* 2023[14]	Parallel	N/A	5/11	Control	Inlay	Particulate xenograft	Bovine xenograft	Not used	Microplate and microscrew fixation	0.518
				Test	Inlay	Particulate xenograft	Bovine xenograft	Not used	Simultaneous implant placement for fixation	
Bianchi *et al.* 2008[15]	Parallel	42 (25 to 55)	3/2	Control	DO	N/A	N/A	N/A	N/A	0.003
		47 (30 to 55)	3/3	Test	Inlay	Block autograft	Medial surface of iliac crest	Not used	Miniplate and miniscrew fixation	
Byun *et al.* 2020a[16]	Parallel	57.86±13.22	14/7	Control	GBR	Particulate xenograft	Bovine xenograft	Titanium-reinforced d-PTFE	N/A	N/A
		54.35±13.99	10/7	Test (TEG)	GBR	Particulate xenograft	Bovine xenograft	Titanium-reinforced d-PTFE	Soft tissue expansion before GBR (TEG)	
		57.63±10.38	6/13	Test (TET)	GBR	Particulate xenograft	Bovine xenograft	Collagen membrane	Soft tissue expansion before GBR with tunneling technique (TET)	
Byun *et al.* 2020b[17]	Parallel	61.13±11.13	15/8	Control	GBR	Particulate xenograft	Bovine xenograft	Titanium-reinforced d-PTFE	No soft tissue expansion. Tenting screws were used in some cases.	N/A
		54.13±12.66	9/14	Test (TET)	GBR	Particulate xenograft	Bovine xenograft	Collagen membrane	Soft tissue expansion before GBR with tunneling technique (TET)	
Chiapasco *et al.* 2004[18]	Parallel	35 (18 to 55)	N/A	Control	DO	N/A	N/A	N/A	N/A	N/A
		48 (31 to 57)	N/A	Test (A)	GBR	Particulate autograft	Chin and/or ramus of mandible	Titanium-reinforced e-PTFE	Simultaneous implant placement for supporting membrane	
		39 (28 to 59)	N/A	Test (B)	GBR	Particulate autograft	Chin and/or ramus of mandible	Titanium-reinforced e-PTFE	Titanium screws for supporting membrane	
Chiapasco *et al.* 2007[19]	Parallel	42 (18 to 55)	6/3	Control	DO	N/A	N/A	N/A	N/A	N/A
		46 (30 to 57)	2/6	Test	Onlay	Block autograft, filled gap with cancellous bone or milled cortical bone remnant	Ramus of mandible using fissure bur and chisels	Not used	Titanium miniscrew fixation	
Cucchi *et al.* 2017[20]	Parallel	52	13/27	Control	GBR	50% particulate autograft, 50% particulate allograft	External oblique ridge of mandible using bone scraper, allograft	Titanium mesh, cross-linked collagen membrane	Simultaneous implant placement	0.58
				Test	GBR	50% particulate autograft, 50% particulate allograft	External oblique ridge of mandible using bone scraper, allograft	Titanium-reinforced d-PTFE	Simultaneous implant placement	

GBR: Guided bone regeneration; DO: Distraction osteogenesis; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; d-PTFE: dense polytetrafluoroethylene; e-PTFE: expanded polytetrafluoroethylene; N/A: Not applicable

Table 1: Characteristics of included studies (continue 1).

Author (year)	Type of RCT	Mean age ± SD or median age (Min to Max) (years)	Male/ female	Treatment arm	Technique	Bone grafting material	Source of bone	Membrane	Special procedure	*p* value between groups of final VBG
Cucchi *et al.* 2021[21]	Parallel	N/A	7/8	Control	GBR	50% particulate autograft, 50% particulate xenograft	Posterior mandible using bone scraper, porcine xenograft	Custom made titanium mesh	N/A	0.11
			8/7	Test	GBR	50% particulate autograft, 50% particulate xenograft	Posterior mandible using bone scraper, porcine xenograft	Custom made titanium mesh, cross-linked collagen membrane	N/A	
Cucchi *et al.* 2024[22]	Parallel	59 (30 to 70)	9/16	Control	GBR	50% particulate autograft, 50% particulate xenograft	Autograft source N/A but using bone scraper, bovine xenograft	Titanium-reinforced d-PTFE, collagen membrane	Titanium-reinforced d-PTFE was adapted to augmented 3D model before applied to surgical site	0.233
			5/20	Test	GBR	50% particulate autograft, 50% particulate xenograft	Autograft source N/A but using bone scraper, bovine xenograft	Custom made titanium mesh, collagen membrane	N/A	
El Zahwy *et al.* 2019[23]	Parallel	38 (24 to 47)	6/2	Control	Onlay	Block autograft, filled gap with milled cancellous bone	Chin	Not used	Block graft fixed with implants	N/A
		39 (31 to 48)	4/4	Test	Inlay	Block autograft, filled gap with milled cancellous bone	Chin	Not used	Block graft fixed with implants	
Felice *et al.* 2008[24]	Split-mouth	54 (32 to 73)	4/6	Control	Inlay	Block autograft, filled gap with particulate iliac bone	Iliac crest	Collagen membrane	Miniplate and miniscrew fixation	N/A
				Test	Inlay	Block xenograft, filled gap with particulate xenograft from block	Bovine xenograft	Collagen membrane	Miniplate and miniscrew fixation	
Felice *et al.* 2009[25]	Parallel	54.5 (39 to 63)	2/8	Control	Onlay	Block autograft, filled gap with particulate iliac bone	Iliac crest	Collagen membrane	Titanium miniscrew fixation	0.19
		55.5 (30 to 75)	4/6	Test	Inlay	Block autograft, filled gap with particulate iliac bone	Iliac crest	Collagen membrane	Miniplate and miniscrew fixation	
Felice *et al.* 2024[26]	Parallel	56.37±10.14	12/15	Control	GBR	80% particulate autograft, 20% particulate xenograft	Ramus of mandible using bone scraper, porcine xenograft	Titanium-reinforced PTFE	N/A	0.867
				Test (Mesh)	GBR	80% particulate autograft, 20% particulate xenograft	Ramus of mandible using bone scraper, porcine xenograft	Custom made titanium mesh	N/A	
				Test (Foil)	GBR	80% particulate autograft, 20% particulate xenograft	Ramus of mandible using bone scraper, porcine xenograft	Custom made titanium foil	N/A	
Fontana *et al.* 2008[27]	Split-mouth	55 (47 to 66)	0/5	Control	GBR	Particulate autograft	Retromolar region	Titanium-reinforced e-PTFE	Tenting screw and mini-implant support membrane	N/A
				Test	GBR	Particulate allograft	Allogeneic bone matrix	Titanium-reinforced e-PTFE	Tenting screw and mini-implant support membrane	

GBR: Guided bone regeneration; DO: Distraction osteogenesis; d-PTFE: dense polytetrafluoroethylene; e-PTFE: expanded polytetrafluoroethylene; N/A: Not applicable

Table 1: Characteristics of included studies (continue 2).

Author (year)	Type of RCT	Mean age ± SD or median age (Min to Max) (years)	Male/ female	Treatment arm	Technique	Bone grafting material	Source of bone	Membrane	Special procedure	*p* value between groups of final VBG
Giragosyan *et al.* 2024[28]	Parallel	N/A	N/A	Control	GBR	50% particulate autograft, 50% particulate xenograft	Oblique line of mandible using bone scraper, xenograft	Titanium-reinforced d-PTFE	N/A	0.4
				Test	GBR	50% particulate autograft, 50% particulate xenograft	Oblique line of mandible using bone scraper, xenograft	Custom made titanium mesh	N/A	
Helal *et al.* 2025[29]	Split-mouth	47 (36 to 56)	4/6	Control	Onlay	CAD/CAM allograft block	Allograft bone block	Nonporous d-PTFE	Bone block hydrated with saline, titanium screw fixation	0.0001
				Test	Onlay	CAD/CAM allograft block	Allograft bone block	Nonporous d-PTFE	Bone block hydrated with hyaluronic acid, titanium screw fixation	
Kawakami *et al.* 2013[30]	Split-mouth	52.1	3/9	Control	Inlay	Block autograft, filled gap with particulate autograft	Intraoral bone	Not used	Titanium osteosynthesis miniplates and miniscrews fixation	>0.05
				Test	Inlay	Mix of alloplast powder and pellet	resorbable non-ceramic hydroxylapatite (ncHA)	Not used	Titanium osteosynthesis miniplates and miniscrews fixation	
Leong *et al.* 2015[31]	Parallel	59.4 ± 7.5	10/6	Control	GBR	Particulate cancellous allograft (on ridge), particulate cortical allograft (second layer)	Cancellous allograft, cortical allograft	Collagen membrane	Tenting screws for supporting membrane	0.305 (Clinical)
				Test	Onlay	Block allograft	Block allograft	Collagen membrane	Titanium screw fixation (2 or more)	0.321 (CBCT)
Maiorana *et al.* 2021[32]	Split-mouth	54.2 ± 12.5	1/4	Control	GBR	50% particulate autograft, 50% particulate xenograft	Retromolar region using bone scraper, bovine xenograft	Titanium mesh	Tenting screw and mini-implant support membrane	0.1
				Test	GBR	50% particulate autograft, 50% particulate xenograft	Retromolar region using bone scraper, bovine xenograft	Titanium-reinforced d-PTFE	Tenting screw and mini-implant support membrane	
Merli *et al.* 2007[33]	Parallel	49.9 (36 to 69)	1/10	Control	GBR	Particulate autograft	Various intraoral bone	Titanium-reinforced e-PTFE	Simultaneous implant placement	0.58
		44.6 (29 to 59)	3/8	Test	GBR	Particulate autograft	Various intraoral bone	Collagen membrane	Simultaneous implant placement, osteosynthesis plates and screws for supporting membrane	
Morad *et al.* 2013[34]	Split-mouth	55.8 (49 to 62)	2/4	Control	Onlay	Block autograft (double layer), covered with particulate xenograft	Ramus of mandible using fissure bur, bovine xenograft	Not used	Screws fixation	0.051
				Test	GBR	Block autograft as cortical tenting, filled internal space with 50% particulate autograft and 50% xenograft	Ramus of mandible using fissure bur (for block), particulate autograft harvested from area of harvested block, bovine xenograft	Not used	Screws fixation	

GBR: Guided bone regeneration; DO: Distraction osteogenesis; d-PTFE: dense polytetrafluoroethylene; e-PTFE: expanded polytetrafluoroethylene; N/A: Not applicable

Table 1: Characteristics of included studies (continue 3).

Author(year)	Type of RCT	Mean age ± SD or median age (Min to Max) (years)	Male/ female	Treatment arm	Technique	Bone grafting material	Source of bone	Membrane	Special procedure	*p* value between groups of final VBG
Moussa *et al.* 2024[35]	Split-mouth	44.7±7.35	4/6	Control	Inlay	Particulate xenograft	Bovine xenograft	Not used	Conventional technique	0.001
				Test	Inlay	Particulate xenograft	Bovine xenograft	Not used	Two patient-specific guides for. osteotomy and fixation	
Moustafa *et al.* 2025[36]	Split-mouth	38.2±2.39	6/4	Control	GBR	50% particulate autograft, 50% particulate xenograft	Symphysis of mandible using Auto Chip Maker bur, bovine xenograft	Titanium mesh	N/A	0.095
				Test	GBR	Particulate xenograft	Bovine xenograft	Titanium mesh	Particulate xenograft mixed with bone marrow aspirate concentrate (BMAC)	
Roccuzzo *et al.* 2007[37]	Parallel	49 (20 to 60)	3/9	Control	Onlay	Block autograft, filled gap with particulate autograft	Ramus and angle of mandible	Not used	Titanium screw fixation	N/A
		50.5 (34 to 68)	4/8	Test	Onlay	Block autograft, filled gap with particulate autograft	Ramus and angle of mandible	Titanium mesh	Titanium screw fixation	
Ronda *et al.* 2014[38]	Parallel	49.6±11.6	1/22	Control	GBR	50% particulate autograft, 50% particulate allograft	Autograft source N/A but collected using bone scraper, allograft	Titanium-reinforced e-PTFE	Simultaneous implant placement	N/A
				Test	GBR	50% particulate autograft, 50% particulate allograft	Autograft source N/A but collected using bone scraper, allograft	Titanium-reinforced d-PTFE	Simultaneous implant placement	
Shaker *et al.* 2024[39]	Parallel	N/A	8/8	Control	GBR	50% particulate autograft, 50% particulate xenograft	Autograft source N/A but collected using bone scraper, bovine xenograft	Titanium-reinforced PTFE	N/A	0.569
				Test	GBR	Autogenous cortical bone shell, 50% particulate autograft, 50% particulate xenograft	External oblique ridge using piezo/surgical disc and bone scraper, bovine xenograft	Not used	Khoury's bone shell technique	
Shomurodov *et al.* 2023[40]	Parallel	44.5±3.6	12/8	Control	GBR	50% particulate autograft, 50% particulate xenograft	Retromolar region, porcine xenograft	N/A	N/A	<0.05
		45.3±3.8	9/9	Test	GBR	50% particulate autograft, 50% particulate xenograft	Retromolar region, porcine xenograft	N/A	Soft tissue expansion before GBR	
Urban *et al.* 2025[41]	Parallel	51.2±10.6	5/10	Control	GBR	50% particulate autograft, 50% particulate xenograft	Autograft from adjacent grafting area using bone scraper, bovine xenograft	Titanium-reinforced d-PTFE	N/A	0.68
			4/11	Test	GBR	50% particulate autograft, 50% particulate xenograft	Autograft from adjacent grafting area using bone scraper, bovine xenograft	Titanium-reinforced d-PTFE, collagen membrane	N/A	

GBR: Guided bone regeneration; DO: Distraction osteogenesis; d-PTFE: dense polytetrafluoroethylene; e-PTFE: expanded polytetrafluoroethylene; N/A: Not applicable

Table 2: Alveolar ridge measurements following vertical bone augmentation with distraction osteogenesis.

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Bianchi *et al.* 2008[15]	Control	5 (0/0/0/5)	16 (0/0/0/16)	10.36±2.96	3 to 4	1.98±1.34	8.38±1.74	CBCT
Chiapasco *et al.* 2004[18]	Control	10 (Maxilla/Mandible=1/9)	34 (1/3/12/18)	6.58±1.38	2 to 3	0.37±0.40	N/A	Periapical film
Chiapasco *et al.* 2007[19]	Control	9 (0/0/0/9)	21 (0/0/7/14)	5.33±1.58	2 to 3	0.30±0.30	N/A	Periapical film

VBG: Vertical bone gain; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 3: Alveolar ridge measurements following vertical bone augmentation with inlay bone grafting.

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Al-Dubai *et al.* 2023[14]	Control	8 (8/0/0/0) 8 (8/0/0/0)	18 (18/0/0/0) 17 (17/0/0/0)	N/A N/A	4 4	N/A N/A	3.86±0.52 4.04±0.59	CBCT
Bianchi *et al.* 2008[15]	Test	7 (0/0/0/7)	21 (0/0/0/21)	5.91±0.76	3 to 4	0.89±0.27	5.03±0.58	CBCT
El Zahwy *et al.* 2019[23]	Test	8 (8/0/0/0)	20 (20/0/0/0)	N/A	6	1.65±0.94	3.34±1.20	CBCT
Felice *et al.* 2008[24]	Control Test	10 (0/0/0/10) 10 (0/0/0/10)	Total 38 both control and test	5.10±1.10 6.20±2.20	4 4	1.10±1.80 0.60±0.40	N/A N/A	CBCT
Felice *et al.* 2009[25]	Test	10 (0/0/0/10)	20 (0/0/0/20)	5.24±1.11	3 to 4	0.72±0.80	4.52±1.19	CBCT
Kawakami *et al.* 2013[30]	Control Test	11 (0/0/0/11) 11 (0/0/0/11)	22 (0/0/0/22) 22 (0/0/0/22)	N/A N/A	6 6	N/A N/A	6.50±2.40 7.00±1.76	CBCT
Moussa *et al.* 2024[35]	Control Test	10 (0/0/0/10) 10 (0/0/0/10)	Total 40 both control and test	N/A N/A	4 4	N/A N/A	2.69±0.37 3.76±0.72	CBCT

VBG: Vertical bone gain; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 4: Alveolar ridge measurements following vertical bone augmentation with onlay bone grafting.

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Abrahamsson *et al.* 2012[13]	Control	10 (10/0/0/0)	13 (13/0/0/0)	2.90±0.90	6	1.30±1.16	1.60±0.80	Clinical
Chiapasco *et al.* 2007[19]	Test	8 (0/0/0/8)	19 (0/0/0/19)	5.00±1.07	4 to 5	0.60±0.70	N/A	Periapical film
El Zahwy *et al.* 2019[23]	Control	8 (8/0/0/0)	20 (20/0/0/0)	N/A	6	4.77±1.67	-0.02±1.86	CBCT
Felice *et al.* 2009[25]	Control	10 (0/0/0/10)	23 (0/0/0/23)	6.52±1.11	3 to 4	2.88±1.13	3.64±1.05	CBCT
Helal *et al.* 2025[29]	Control	10 (0/0/0/10) 10 (0/0/0/10)	N/A N/A	N/A N/A	6 6	N/A N/A	2.497±0.66 3.947±0.31	CBCT
Leong *et al.* 2015[31]	Test	9 (0/0/0/9)	N/A	N/A	6	N/A	Clinical 1.78 (range 0 to 5) CBCT 1.96 (range 0 to 5.19)	Clinical and CBCT
Morad *et al.* 2013[34]	Control	6 (0/0/0/6)	N/A	6.07±1.20	4	1.58±1.11	4.48±0.52	Panoramic film
Roccuzzo *et al.* 2007[37]	Control Test	12 (2/0/1/9) 12 (2/6/0/4)	25 (5/0/2/18) 28 (3/15/0/10)	5.50±1.20 5.70±1.50	4 to 6 4 to 6	1.90±1.10 0.90±0.80	3.60±1.40 4.80±1.50	Clinical

VBG: Vertical bone gain; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 5: Alveolar ridge measurements following vertical bone augmentation with guided bone regeneration.

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Abrahamsson *et al.* 2012[13]	Test	10 (9/0/0/1)	10 (9/0/0/1)	4.10±1.70	6	1.10±1.60	3.00±1.40	Clinical
Byun *et al.* 2020a[16]	Control Test (TEG) Test (TET)	21 (Maxilla/Mandible=12/9) 17 (Maxilla/Mandible=5/12) 19 (Maxilla/Mandible=13/6)	N/A N/A N/A	4.32±0.97 5.71±1.99 5.13±1.32	6 6 6	2.06±1.00 1.16±0.62 1.54±0.12	N/A N/A N/A	CBCT
Byun *et al.* 2020b[17]	Control Test	23 (Maxilla/ Mandible=13/10) 23 (Maxilla/ Mandible=13/10)	N/A N/A	4.22±1.15 5.12±1.25	6 6	2.32±1.09 1.57±1.03	N/A N/A	CBCT
Chiapasco *et al.* 2004[18]	Test (A) Test (B)	6 (Maxilla/Mandible=1/5) 5 (Maxilla/Mandible=4/1)	13 (1/0/3/9) 12 (5/4/0/3)	4.50±1.38 5.08±1.06	6 to 7 6 to 7	1.27±0.80 1.35±0.90	N/A N/A	Periapical film
Cucchi *et al.* 2017[20]	Control Test	19 (0/0/0/19) 20 (0/0/0/20)	Total 108 both control and test	4.00±0.08 3.80±0.70	9 9	-0.20±0.70 -0.50±0.60	4.10±1.00 4.20±1.00	Clinical
Cucchi *et al.* 2021[21]	Control Test	15 (Maxilla/Mandible=5/10) 15 (Maxilla/Mandible=9/6)	34 (N/A) 37 (N/A)	N/A N/A	6 6	N/A N/A	4.74±2.56 6.36±2.31	CBCT
Cucchi *et al.* 2024[22]	Control Test	24 (Maxilla/ Mandible=10/14) 24 (Maxilla/ Mandible=12/12)	55 (N/A) 60 (N/A)	6.08±1.77 5.59±1.68	6 (Mandible) 9 (Maxilla) 6 (Mandible) 9 (Maxilla)	N/A N/A	5.79±1.71 5.18±1.61	CBCT

VBG: Vertical bone gain; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 5: Alveolar ridge measurements following vertical bone augmentation with guided bone regeneration (continue 1).

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Felice *et al.* 2024[26]	Control Test (Mesh) Test (Foil)	9 (N/A) 9 (N/A) 9 (N/A)	19 (N/A) 20 (N/A) 21 (N/A)	N/A N/A N/A	8 8 8	N/A N/A N/A	6.53±0.73 6.86±0.94 6.81±2.13	CBCT
Fontana *et al.* 2008[27]	Control Test	5 (0/0/0/5) 5 (0/0/0/5)	12 (0/0/0/12) 13 (0/0/0/13)	4.90±0.93 5.15±0.34	6 6	0.80±1.08 0.45±0.37	4.10±0.88 4.70±0.48	Clinical
Giragosyan *et al.* 2024[28]	Control Test	20 (N/A) 20 (N/A)	N/A N/A	N/A N/A	6 6	N/A N/A	4.24±2.19 3.65±1.73	CBCT
Leong *et al.* 2015[31]	Control	10 (0/0/0/10)	N/A	N/A	6	N/A	Clinical 1 (range -1 to 3) CBCT 0.96 (range -2 to 5.14)	Clinical and CBCT
Maiorana *et al.* 2021[32]	Control Test	5 (0/0/0/5) 5 (0/0/0/5)	10 (0/0/0/10) 11 (0/0/0/11)	3.40±1.00 4.20±1.70	8 8	1.90±1.50 -0.05±0.60	1.50±1.60 4.20±2.20	Clinical
Merli *et al.* 2007[33]	Control Test	11 (Maxilla/Mandible=0/11) 11 (Maxilla/Mandible=1/10)	55 (N/A) 42 (N/A)	2.73±0.79 2.93±0.86	4.6 4.6	0.25±0.62 0.77±1.25	2.48±1.13 2.16±1.51	Clinical
Morad *et al.* 2013[34]	Test	6 (0/0/0/6)	N/A	6.37±0.71	4	1.17±0.41	5.20±0.76	Panoramic film

VBG: Vertical bone gain; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 5: Alveolar ridge measurements following vertical bone augmentation with guided bone regeneration (continue 2).

Author (year)	Treatment arm	Number of surgical sites (AMX/PMX/AMD/PMD)	Number of implants (AMX/PMX/AMD/PMD)	VBG (immediate post-op) (mm)	Healing period (months)	Resorption (complete healing period) (mm)	Final VBG (complete healing period) (mm)	Measurement method
Moustafa *et al.* 2025[36]	Control Test	10 (Maxilla/Mandible=10/0) 10 (Maxilla/Mandible=10/0)	Total 60 both control and test N/A	N/A N/A	6 6	N/A N/A	4.10±0.67 3.47±0.87	CBCT
Ronda *et al.* 2014[38]	Control Test	13 (0/0/0/13) 13 (0/0/0/13)	40 (0/0/0/40) 38 (0/0/0/38)	4.10±1.86 4.70±1.69	6 to 7 6 to 7	-0.81±0.74 -0.80±0.76	4.91±1.78 5.49±1.58	Clinical
Shaker *et al.* 2024[39]	Control Test	8 (0/0/0/8) 8 (0/0/0/8)	N/A N/A	N/A N/A	6 6	N/A N/A	3.56±1.12 4.20±0.46	CBCT
Shomurodov *et al.* 2023[40]	Control Test	20 (Maxilla/Mandible=8/12) 18 (Maxilla/Mandible=6/12)	Total 96 both control and test	4.75±0.16 5.85±0.42	6 6	2.01±0.15 1.78±0.12	2.70±0.14 4.07±0.30	CBCT
Urban *et al.* 2025[41]	Control Test	15 (Maxilla/Mandible=5/10) 15 (Maxilla/Mandible=8/7)	N/A N/A	N/A N/A	9 9	N/A N/A	4.47±2.05 4.11±2.69	CBCT

VBG: Vertical bone gain; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; AMX: Anterior maxilla; PMX: Posterior maxilla; AMD: Anterior mandible; PMD: Posterior mandible; CBCT: Cone beam computed tomography; N/A: Not applicable.

Table 6: Complications and implant success and survival rates.

Author (year)	Control (Number of sites, implants)	Test (Number of sites, implants)	Complications Control	Complications Test	Implant survival Control (%)	Implant survival Test (%)	Implant success Control (%)	Implant success Test (%)
Abrahamsson *et al.* 2012[13]	Onlay (10,13)	GBR (10,10)	None	Minor perforation during soft tissue expansion = 2 Titanium mesh exposure after GBR = 2 (Overall rate = 40%)	N/A	N/A	N/A	N/A
Al-Dubai *et al.* 2023[14]	Inlay (8,18)	Inlay (8,17)	Crack of bone fragment during screw fixation = 1 (Overall rate = 12.5%)	None	N/A	N/A	N/A	N/A
Bianchi *et al.* 2008[15]	DO (5,16)	Inlay (7,21)	Minor local infection = 1 Progressive lingual proclination = 2 (Overall rate = 60%)	Post-surgical dehiscence = 1 (Overall rate = 14.29%)	100	100	93.7 (at 1 year)	95.2 (at 1 year)
Byun *et al.* 2020a[16]	GBR (21,N/A)	GBR (TEG) (17,N/A)	None	Over soft tissue expansion (silicone envelope tearing) = 1 (Overall rate = 5.88%)	N/A	N/A	N/A	N/A
		GBR (TET) (19,N/A)	Mucosal perforation during soft tissue expansion) = 1 Over soft tissue expansion (silicone envelop tearing) = 2 (Overall rate = 15.79%)			N/A		N/A
Byun *et al.* 2020b[17]	GBR (23,N/A)	GBR (TET) (23,N/A)	Early wound dehiscence after bone grafting = 2 (Overall rate = 8.7%)	Over soft tissue expansion (silicone envelope tearing) = 2 Mucosal perforation during soft tissue expansion = 1 (Overall rate = 13.04%)	N/A	N/A	N/A	N/A
Chiapasco *et al.* 2004[18]	DO (10,34)	GBR (A) (6,13)	Lingual inclination bone fragment = 2 (Overall rate = 20%)	Membrane exposure without infection = 1 Membrane exposure with infection = 1 (Overall rate = 33.33%)	100	100	100 (at 1 year) 100 (at 1-2 year) 94.1 (at 2-3 year)	84.6 (at 1 year) 76.9 (at 1-2 year) 61.5 (at 2-3 year)
		GBR (B) (5,12)		Paresthesia at chin = 1 Paresthesia at chin and membrane exposure = 1 (Overall rate = 40%)		100		83.3 (at 1 year) 83.3 (at 1-2 year) 75 (at 2-3 year)
Chiapasco *et al.* 2007[19]	DO (9,21)	Onlay (8,19)	Lingual inclination distracted bone fragment = 2 Incomplete distraction = 1 (Overall rate = 33.33%)	Partial graft loss due to graft exposure = 1 Transient paresthesia = 2 Permanent paresthesia = 1 (Overall rate = 50%)	100	100	100 (at 1 year) 94.7 (at 1-2 year) 94.7 (at 2-3 year) 94.7 (at 3-4 year) 94.7 (at 4-5 year)	89.5 (at 1 year) 89.5 (at 1-2 year) 89.5 (at 2-3 year) 89.5 (at 3-4 year) 89.5 (at 4-5 year)
Cucchi *et al.* 2017[20]	GBR (19,N/A)	GBR (20,N/A)	Temporary paresthesia = 3 Abscess without exposure = 1 Early exposure with infection = 1 Late exposure with infection = 1 Late exposure without infection = 1 (Overall rate = 36.84%)	Temporary paresthesia = 1 Abscess without exposure = 1 Early exposure with infection = 1 Late exposure without infection = 1 (Overall rate = 20%)	N/A	N/A	N/A	N/A
Cucchi *et al.* 2021[21]	GBR (15,34)	GBR (15,37)	Surgical/technical complications = 2 Healing complications = 5 (Overall rate = 46.67%)	Surgical/technical complications = 4 Healing complications = 2 (Overall rate = 40%)	94	97	N/A	N/A

GBR: Guided bone regeneration; DO: Distraction osteogenesis; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; N/A: Not applicable

Table 6: Complications and implant success and survival rates (continue 1).

Author (year)	Control (Number of sites, implants)	Test (Number of sites, implants)	Complications Control	Complications Test	Implant survival Control (%)	Implant survival Test (%)	Implant success Control (%)	Implant success Test (%)
Cucchi *et al.* 2024[22]	GBR (24,55)	GBR (24,60)	Flap perforation = 1 Early exposure without infection = 1 Late exposure without infection = 1 Abscess without exposure = 1 Complete graft loss = 1 Partial graft loss = 2 (Overall rate = 29.17%)	Flap perforation = 1 Transient paresthesia = 2 Early exposure with infection = 1 Abscess without exposure = 1 Complete graft loss = 1 Partial graft loss = 1 (Overall rate = 29.17%)	N/A	N/A	N/A	N/A
El Zahwy *et al.* 2019[23]	Onlay (8,20)	Inlay (8,20)	Crack of block autograft during implant placement = 1 Mobility of graft and loss of implant = 3 Complete loss of autograft = 2 Implant thread exposure = 1 (Overall rate = 87.5%)	None	N/A	N/A	N/A	N/A
Felice *et al.* 2008[24]	Inlay (10,N/A)	Inlay (10,N/A)	Buccal dehiscence = 1 Bone graft fracture and wound dehiscence = 1 (Overall rate = 20%)	Lingual dehiscence = 1 (lingual soft tissue perforation from pie-zo-electric instrument) (Overall rate = 10%)	N/A	N/A	N/A	N/A
Felice *et al.* 2009[25]	Onlay (10,23)	Inlay (10,20)	Dehiscence = 2 Infection = 1 Temporary hypoesthesia = 2 (Overall rate = 50%)	Dehiscence = 3 Temporary hypoesthesia = 4 (Overall rate = 70%)	100	100	86.9 (13-22 months)	90 (17-22 months)
Felice *et al.* 2024[26]	GBR (9,19)	GBR (Mesh) (9,20)	Transient paresthesia = 1 Peri-implant mucositis = 1 (Overall rate = 22.22%)	Transient paresthesia = 1 Device exposure = 1 Implant lack of integration = 1 (Overall rate = 33.33%)	N/A	N/A	N/A	N/A
		GBR (Foil) (9,21)		Device exposure = 1 Deficient of regenerated bone = 1 (Overall rate = 22.22%)	N/A	N/A	N/A	N/A
Fontana *et al.* 2008[27]	GBR (5,12)	GBR (5,13)	Paresthesia = 1 Infection without dehiscence = 1 (Overall rate = 40%)	Temporary paresthesia = 1 Buccal bone dehiscence =1 (Overall rate = 40%)	N/A	N/A	N/A	N/A
Giragosyan *et al.* 2024[28]	GBR (20,N/A)	GBR (20,N/A)	Overall rate = 38.9%	Overall rate = 33.3%	N/A	N/A	N/A	N/A
Helal *et al.* 2025[29]	Onlay (10,N/A)	Onlay (10,N/A)	Transient paresthesia = 1 Dehiscence without infection = 2 (Overall rate = 30%)	Transient paresthesia = 1 Minor gingival edema and erythema = 1 (Overall rate = 20%)	N/A	N/A	N/A	N/A
Kawakami *et al.* 2013[30]	Inlay (11,22)	Inlay (11,22)	Titanium miniplate exposure =1 Temporary neurosensory disturbance = 6 (Overall rate = 63.64%)	Titanium miniplate exposure =1 Temporary neurosensory disturbance = 6 (Overall rate = 63.64%)	N/A	N/A	N/A	N/A
Leong *et al.* 2015[31]	GBR (10,N/A)	Onlay (9,N/A)	Wound dehiscence = 3 (Overall rate = 30%)	Wound dehiscence = 7 Graft failure = 1 (Overall rate = 88.89%)	N/A	N/A	N/A	N/A

GBR: Guided bone regeneration; DO: Distraction osteogenesis; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; N/A: Not applicable

Table 6: Complications and implant success and survival rates (continue 2).

Author (year)	Control (Number of sites, implants)	Test (Number of sites, implants)	Complications Control	Complications Test	Implant survival Control (%)	Implant survival Test (%)	Implant success Control (%)	Implant success Test (%)
Maiorana *et al.* 2021[32]	GBR (5,10)	GBR (5,11)	Titanium mesh exposure = 2 (Overall rate = 40%)	None	N/A	N/A	N/A	N/A
Merli *et al.* 2007[33]	GBR (11,55)	GBR (11,42)	Fistula (abutment connection) = 1 Fistula (2 weeks post surgery) = 1 Fistula (2 months post surgery) = 1 Lymph node swelling (1 month post surgery) = 1 Dehiscence with infection and graft failure = 1 (Overall rate = 45.45%)	Dehiscence without pus = 1 Swelling and infection = 1 Abscess and graft failure = 2 (Overall rate = 36.36%)	N/A	N/A	N/A	N/A
Morad *et al.* 2013[34]	Onlay (6,N/A)	GBR (6,N/A)	None	None	N/A	N/A	N/A	N/A
Moussa *et al.* 2024[35]	Inlay (10,N/A)	Inlay (10,N/A)	Transient paresthesia = 10 (Overall rate = 100%)	Soft tissue dehiscence and transient paresthesia = 1 Transient paresthesia = 9 (Overall rate = 100%)	N/A	N/A	N/A	N/A
Moustafa *et al.* 2025[36]	GBR (10,N/A)	GBR (10,N/A)	Soft tissue dehiscence = 1 (Overall rate = 10%)	None	N/A	N/A	N/A	N/A
Roccuzzo *et al.* 2007[37]	Onlay (12,25)	Onlay (12,28)	Incomplete integration of graft = 3 Graft mobility during implant placement = 1 Temporary paresthesia = 1 Significant graft resorption = 2 (Overall rate = 58.33%)	Titanium mesh exposure = 4 (Overall rate = 33.33%)	N/A	N/A	N/A	N/A
Ronda *et al.* 2014[38]	GBR (13,40)	GBR (13,38)	None	None	N/A	N/A	N/A	N/A
Shaker *et al.* 2024[39]	GBR (8,N/A)	GBR (8,N/A)	None	Wound dehiscence = 1 (Overall rate = 12.5%)	N/A	N/A	N/A	N/A
Shomurodov *et al.* 2023[40]	GBR (20,N/A)	GBR (18,N/A)	Early wound dehiscence = 2 Temporary hypoesthesia = 4 (Overall rate = 30%)	Temporary hypoesthesia = 1 (Overall rate = 5.56%)	N/A	N/A	N/A	N/A
Urban *et al.* 2025[41]	GBR (15,N/A)	GBR (15,N/A)	Membrane exposure = 1 (Overall rate = 6.67%)	Abscess without exposure = 1 (Overall rate = 6.67%)	N/A	N/A	N/A	N/A

GBR: Guided bone regeneration; DO: Distraction osteogenesis; TEG: Tissue expansion before GBR; TET: Tissue expansion before GBR with tunneling technique; N/A: Not applicable

Table 7: Summary of outcomes for vertical ridge augmentation techniques.

Augmentation technique	Final vertical bone gain (mm)	Bone resorption (mm)	Complication rate	Key complications	Implant survival rate	Implant success rate (at the longest follow-up time)
Distraction osteogenesis	8.38±1.74	0.30±0.30 to 1.98±1.34	20% to 60%	-Lingual inclination of distracted fragment -Infection -Incomplete distraction	100%	94.7% (at 4-5 years)
Inlay	2.69±0.37 to 7.00±1.76	0.60±0.40 to 1.65±0.94	0% to 100%	-Transient hypoesthesia -Wound dehiscence -Crack of bone fragment -Miniplate exposure	100%	90% (at 17-22 months)
Onlay	1.60±0.80 to 4.80±1.50	0.60±0.70 to 4.77±1.67	0% to 88.89%	-Wound dehiscence -Transient paresthesia -Partial graft loss -Complete graft loss	100%	89.5% (at 4-5 year)
Guided bone regeneration	1.50±1.60 to 6.86±0.94	0.25±0.62 to 2.32±1.09	0% to 46.67%	-Transient paresthesia -Wound dehiscence -Membrane exposure -Infection	94% to 100%	61.5% to 75% (at 2-3 year)

Conclusions

Based on the findings of this study, all vertical bone augmentation techniques can effectively increase the height of the augmented areas. While DO provides the greatest vertical bone gain, it requires a highly experienced surgeon, specialized instruments and complex treatment planning. The more practical technique would be GBR, since it provides high final vertical bone gain, low bone resorption, and the lowest complication rate. In addition, it can be easily modified to use barrier membranes and bone grafting materials to suit individual patients.

Conflict of Interest

The authors declare there is no conflict of interest regarding the publication of this article. The funder did not have any influence on this study.

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