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Prediction of the bone volume for sinus augmentation through 3-dimensional analysis

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Abstract *Background/purpose:* No consensus has been established regarding the exact amount of bone grafting in maxillary sinus augmentation. The aim of this study was to estimate the minimum bone volume for sinus augmentation and to investigate the factors that influence the augmentation volume (AV).
Materials and methods: This study included patients with cone-beam computed tomography scanning. Dome-shaped sinus augmentation was performed virtually at vertical heights (VH) of 3, 5, 7, and 9 mm in Group A (without implantation) and Group B (with implantation). The augmentation angle (AA) and the sinus width (SW) were measured. The AV was measured using the three-dimensional image processing program 3D Slicer. Univariable and multivariable analyses were conducted.
Results: This study included 30 patients (120 subjects). In Group A, the mean AVs were 0.062, 0.271, 0.642, and 1.287 cc at VHs of 3, 5, 7, and 9 mm, respectively, in Group B, the mean AVs were 0.037, 0.230, 0.594, and 1.230 cc. Univariable analysis indicated that factors significantly associated with the AV in both groups included SW, AA, and VH ($P < 0.001$). Multivariable analysis indicated that factors significantly associated with the AV in both groups included AA and VH ($P < 0.01$).
Conclusion: Clinicians can predict the bone volume for sinus augmentation by measuring the augmentation height and angle.

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Introduction

In the maxillary sinus augmentation procedure, there is widespread consensus among clinicians that a sufficient amount of bone substitute is needed, i.e., more than is required to adequately surround the fixture. Advancements in radiographic imaging devices, such as cone-beam computed tomography (CBCT), have made it easier for clinicians to assess the need for maxillary sinus augmentation prior to implant placement. However, a consensus has not been established regarding the exact amount of sinus augmentation, and many clinicians still rely on their own experience to determine the amount of bone grafting. Insufficient bone augmentation increases the likelihood of compromising the stability of the implant, while excessive bone grafting increases the potential for iatrogenic complications such as sinus perforation.[1,2] Therefore, accurate estimation of the required amount of bone augmentation is crucial to enhance the success rate of implants. It is difficult to accurately estimate the required amount of bone augmentation because it is influenced by factors such as the fixture length, sinus morphology, and three-dimensional (3D) amount of sinus membrane elevation necessary to accommodate the implant. The required amount of bone grafting is likely to increase as the height of sinus augmentation increases,[3] although this relationship may not always be consistent. Even if sinus augmentation is performed to achieve the same height, wider maxillary sinuses require more bone grafting.

Several studies have been conducted to measure the amount of bone graft required for sinus augmentation.[4–6] However, these studies are limited in terms of accurate measurement of the minimum bone requirement. Because they only retrospectively calculated the average bone graft volume after arbitrary sinus augmentation or measured the entire volume below the horizontal plane at a specific height within the sinus. To our knowledge, there are no reports comparing maxillary sinus augmentation without and with simultaneous implantation in terms of 3D volume measurements.

The purpose of this study was to determine the amount of bone grafting required for sinus augmentation in the maxillary posterior area using 3D volume analysis. Groups that underwent maxillary sinus augmentation without and with simultaneous implantation were analyzed. Additionally, we attempted to investigate the factors that influence the amount of bone grafting required using the dimensions of the maxillary sinus cavity. We hypothesized that angulation of the sinus lateral wall or the dimensions of the maxillary sinus would influence the augmentation volume (AV).

Materials and methods

Study sample

This retrospective cohort study included all patients who visited the Department of Oral and Maxillofacial Surgery at Seoul Metropolitan Government-Seoul National University Boramae Medical Center (SMG-SNU BMC) (Seoul, Korea) from January 2021 to June 2023. The study was approved by the Institutional Review Board of SMG-SNU BMC (IRB No. 20-2063-62) and was conducted in adherence to the 1964 Helsinki Declaration and its later amendments. Data selection and measurements were performed by one experienced examiner (SY Park, first author).

The inclusion criterion was as follows: patients who underwent CBCT imaging for implant placement with maxillary sinus augmentation in the edentulous posterior maxilla. The exclusion criteria were as follows: (1) patients who had pathologic findings in the maxillary sinus such as sinusitis, tumors, or cysts; (2) patients with unclear CBCT images due to artifacts in maxillary sinus; and (3) patients who had septa in the maxillary sinus floor. Two groups were established: Group A, in which patients underwent maxillary sinus augmentation, and Group B, in which patients underwent maxillary sinus augmentation with simultaneous implantation.

Variables and data collection methods

The predictor variables were the augmentation angle (AA), sinus width (SW), and vertical height (VH). The outcome variable was the AV.

CBCT images of the maxillary sinus were obtained using CS9600 (Carestream Dental LLC, Atlanta, GA, USA). Additionally, a CBCT image of the implant fixture (TS III 4510; Osstem Implant, Seoul, Korea) was obtained as a template for virtual implantation. The implant fixture has a length of 10 mm, a diameter of 4.5 mm on the coronal aspect, and a slope of 1.5°. The acquisition parameters were as follows: scan time of 7 s at 95 kV and 9 mA, a voxel size of 0.3 mm, and a field of view of 9 mm. All images were stored in Digital Imaging and Communication in Medicine (DICOM) format and reconstructed at 0.5 mm thickness using the INFINITT Picture Archiving and Communication System (INFINITT Healthcare, Seoul, Korea).

To perform simultaneous implantation and bone augmentation, a template for the implant was created in a 3D environment. The implant DICOM files were imported into ITK-SNAP 4.0.1 (Penn Image Computing and Science Laboratory, Philadelphia, PA, USA), and a 3D template for

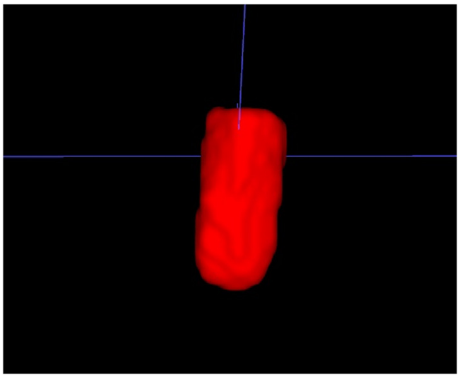

Figure 1 Three-dimensional (3D) reconstruction of the implant fixture.

the virtual implant was created (Fig. 1). To generate 3D reconstructions of maxillary anatomic structures, maxilla DICOM files were imported into 3D Slicer 5.2.1 (Brigham and Women's Hospital, Boston, MA, USA).[7] All images were adjusted to ensure bilateral symmetry of the maxilla, and the occlusal plane was aligned parallel to the ground. After uploading the implant fixture image file, virtual implantation was performed in optimal positions vertical to the occlusal plane in the maxillary posterior region based on the acquired CBCT images. Subsequently, dome-shaped sinus augmentation was performed virtually with VHs of 3, 5, 7, and 9 mm at locations where the fixture was placed. Consequently, the highest point of sinus augmentation was 1 mm higher than the apical end of the implant fixture. The dome was assumed to be spherical, and the center of the spherical (COS) was defined as the point where the long axis of the implant fixture intersected the sinus floor. Its radius was equal to the VH. Additionally, the angles between the sinus floor and the lateral wall were measured in the coronal cut images at locations where the fixtures were placed within each spherical model. The angle formed between the line connecting the COS and the point where the circle met the lateral wall of the maxillary sinus and the long axis of the implant was set as the AA. Additionally, a horizontal line was drawn from the highest point of the sinus augmentation to the lateral wall of the maxillary sinus in the coronal plane. The length of this horizontal line was referred to as the SW (Fig. 2).

In the AV measurement step, anatomical structures such as alveolar bone, the oral cavity, and the nasal cavity were manually removed from the spherical model to ultimately form the augmentation segment. After setting the region of interest (ROI) in the maxillary sinus area, the AV was measured. First, the volume of the dome-shaped sinus augmentation was measured to obtain data for Group A (Fig. 3A and B). Second, the volume excluding the implant fixture from the ROI was measured again for Group B (Fig. 3C and D).

Data analysis

All data analyses were performed using SPSS 26 (SPSS Inc., Chicago, IL, USA). All statistical results were considered significant if the *P*-value was less than 0.05. The Shapiro-Wilk test was used to determine the normality of the data. Pearson correlation analysis was conducted to assess the correlation between the SW and AA. Univariable and multivariable (stepwise regression) analyses were performed to identify variables significantly associated with the AV.

In this study, the term "explanatory power" was employed. This refers to the capacity of a statistical model to effectively elucidate the connection between predictor

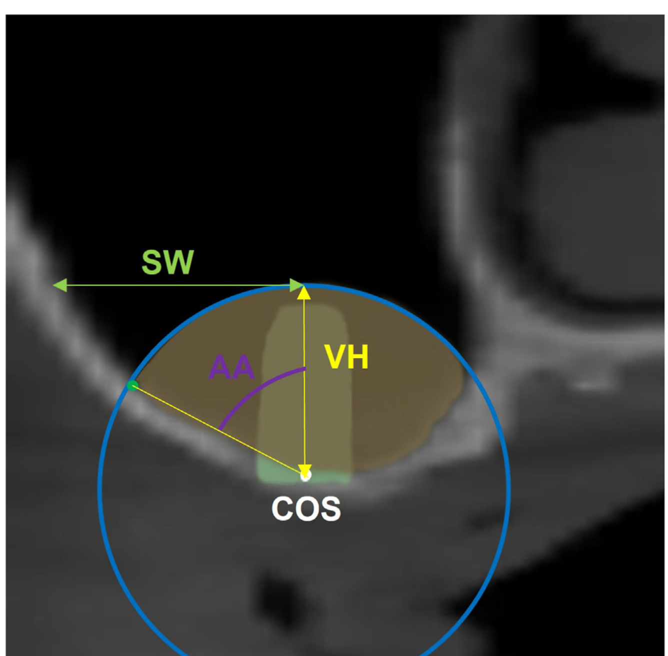

Figure 2 Three-dimensional (3D) virtual augmentation and measurement. COS, center of the spherical; VH, vertical height; AA, augmentation angle; SW, sinus width.

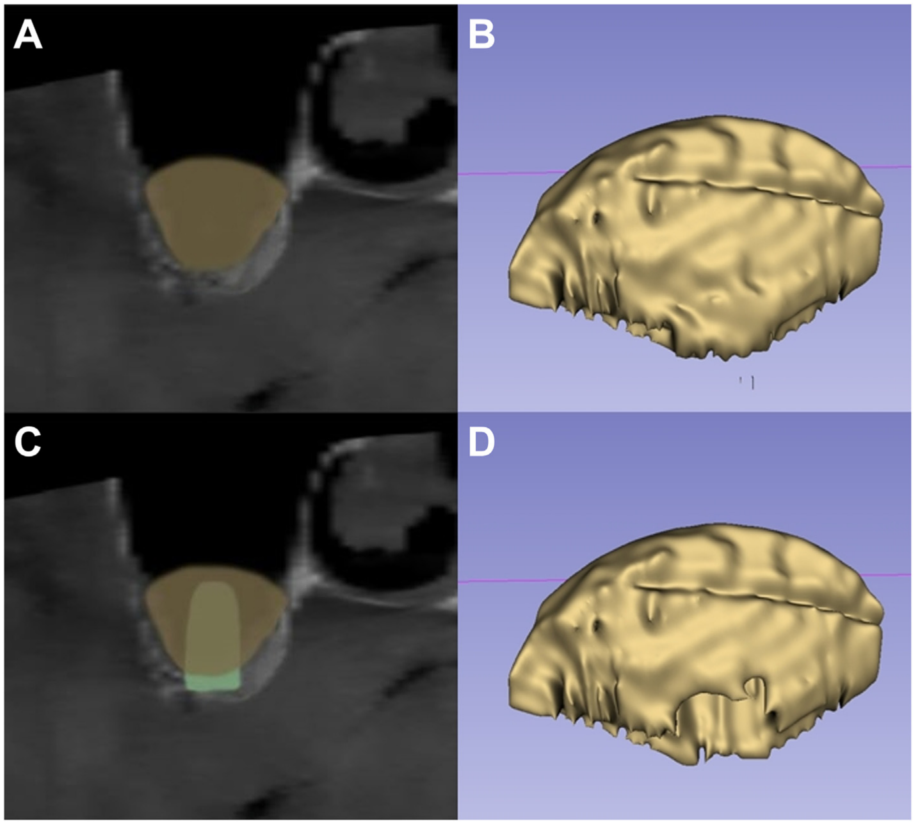

Figure 3 Augmentation volume (AV) measurement. (A) Virtual augmentation image of Group A in the coronal plane. (B) Augmentation volume measurement of Group A. (C) Virtual augmentation image of Group B in the coronal plane. (D) Augmentation volume measurement of Group B.

and outcome variables. The adjusted R^2 is an indicator of the model's ability to provide an explanation.

As a measure of relative reliability, intra-class correlation coefficients (ICCs) were estimated. All subject was measured twice using the same CBCT images, with a 12-week interval.

Results

A total of 30 patients (17 males and 13 females, 120 subjects) were included in the present study. The patients' mean age ± standard deviation (SD) was 66.30 ± 10.02 years. The mean SWs ±SD were 6.20 ± 1.00, 7.94 ± 1.14, 9.28 ± 1.34, and 11.41 ± 1.89 mm at VHs of 3, 5, 7, and 9 mm, respectively. The mean AAs ±SD were 74.36 ± 7.33, 68.77 ± 8.96, 59.32 ± 7.98, and 51.40 ± 6.71° at VHs of 3, 5, 7, and 9 mm, respectively. In Group A, the mean AVs ±SD were 0.062 ± 0.017, 0.271 ± 0.059, 0.642 ± 0.122, and 1.287 ± 0.216 cc at VHs of 3, 5, 7, and 9 mm, respectively. In Group B, the mean AVs ±SD were 0.037 ± 0.015, 0.230 ± 0.056, 0.594 ± 0.118, and 1.230 ± 0.313 cc at VHs of 3, 5, 7, and 9 mm, respectively (Table 1).

The Shapiro-Wilk test results showed that SW, AA, and AV were normally distributed in all VHs (Table 2).

The ICCs ranged from 0.934 to 0.997 for repeat measurements. There were no significant differences between the two measurement sets at a 95 % confidence level ($P < 0.001$) (Table 3).

The Pearson correlation coefficients between the SW and AA were 0.490 ($P < 0.001$), 0.461 ($P < 0.05$), 0.543 ($P < 0.001$), and 0.448 ($P < 0.05$) at VHs of 3, 5, 7, and 9 mm, respectively. As the SW increased, the AA tended to increase (Table 4 and Fig. 4).

Univariable analysis indicated that factors significantly associated with the AV in both groups included SW, AA, and VH ($P < 0.001$) (Table 5). Multivariable analysis indicated that factors significantly associated with the AV in both groups included AA and VH ($P < 0.01$) (Table 6). In Group A, the AV was positively affected by VHs of 23.0 % and AAs of 0.7 % (explanatory power = 89.1 %). In Group B, the AV was positively affected by VHs of 22.9 % and AAs of 0.7 % (explanatory power = 87.7 %).

Discussion

To obtain sufficient alveolar bone for implantation, many clinicians use ridge preservation or ridge augmentation techniques.[8–10] However, total reliance on methods to increase the height of the alveolar crest has limitations, especially in cases with pneumatization of the maxillary sinus. Therefore, efforts aimed at increasing available bone through sinus augmentation have continued to improve long term survival.[11]

The amount of available bone can be increased through maxillary sinus augmentation, which increases the survival rate of implants.[12–14]However, little is known regarding

Table 1 Measurements of the sinus width, augmentation angle, and augmentation volume (N = 30).

Variable	VH, mm			
	3	5	7	9
SW, Mean ± SD, mm (Min–Max)	6.20 ± 1.00 (4.55–8.66)	7.94 ± 1.14 (6.16–9.86)	9.28 ± 1.34 (7.05–11.68)	11.41 ± 1.89 (7.75–15.32)
AA, Mean ± SD, ° (Min–Max)	74.36 ± 7.33 (61.85–89.00)	68.77 ± 8.96 (54.15–88.79)	59.32 ± 7.98 (44.90–74.88)	51.40 ± 6.71 (39.07–63.04)
AV, Mean ± SD, cc (Min–Max)				
Group A	0.062 ± 0.017 (0.045–0.095)	0.271 ± 0.059 (0.186–0.371)	0.642 ± 0.122 (0.415–0.896)	1.287 ± 0.216 (0.930–1.743)
Group B	0.037 ± 0.015 (0.015–0.094)	0.230 ± 0.056 (0.132–0.357)	0.594 ± 0.118 (0.380–0.842)	1.230 ± 0.313 (0.886–1.694)

SW, sinus width; AA, augmentation angle; AV, augmentation volume; VH, vertical height; SD, standard deviation; Min, minimum; Max, maximum.

Table 2 Shapiro-Wilk test of the sinus width, augmentation angle, and augmentation volume (N = 30).

Variables	VH, mm	W	*P*-value
SW	3	0.968	0.475
	5	0.960	0.302
	7	0.958	0.278
	9	0.978	0.773
AA	3	0.954	0.210
	5	0.949	0.157
	7	0.977	0.739
	9	0.957	0.265
AV, Group A	3	0.978	0.773
	5	0.978	0.779
	7	0.983	0.898
	9	0.961	0.334
AV, Group B	3	0.941	0.094
	5	0.971	0.558
	7	0.981	0.846
	9	0.967	0.470

VH, vertical height; SW, sinus width; AA, augmentation angle; AV, augmentation volume.

Table 3 Intra-class correlation coefficients of the sinus width, augmentation angle, and augmentation volume (N = 30).

Variable	VH, mm			
	3	5	7	9
SW	0.983‡	0.982‡	0.934‡	0.977‡
AA	0.989‡	0.997‡	0.965‡	0.952‡
AV, Group A	0.965‡	0.985‡	0.997‡	0.979‡
AV, Group B	0.962‡	0.954‡	0.991‡	0.972‡

SW, sinus width; AA, augmentation angle; AV, augmentation volume; VH, vertical height.
‡$P < 0.001$.

how much bone graft material is required. Therefore, the goal of this study was to calculate the amount of bone graft required for maxillary sinus augmentation that allows an implant fixture of a specific length. We also aimed to analyze the influence of the augmentation height and dimensions of the maxillary sinus on the AV.

Table 4 Pearson correlation coefficients between the augmentation angle and sinus width (N = 30).

	VH, mm			
	3	5	7	9
Pearson correlation coefficient	0.490‡	0.461*	0.543‡	0.448*

VH, vertical height.
*$P < 0.05$.
‡$P < 0.001$.

It can be inferred that as the VH of augmentation increases, the AV also increases. To increase the VH by 3.7 ± 1.08, 4.95 ± 0.88, and 5.84 ± 0.81 mm, 0.1, 0.2, and 0.3 mL of bone graft material is required, respectively.[5] In reality, bone resorption occurs after sinus augmentation; therefore, a larger amount of bone graft material is required during surgery.

When performing maxillary sinus augmentation at the same height, the AV may vary depending on the shape of the maxillary sinus, especially its dimensions. The AV tends to increase as the SW increases, but the SW does not reliably represent the AV. In clinical practice, bone grafting is not performed uniformly in all areas below a certain height, but in a dome shape. The radius of the dome is determined by the VH, and the shape of the dome is determined by the slope of the maxillary sinus wall. Therefore, the AA, which represents the slope of the maxillary sinus wall, was selected as a factor affecting the AV in this study. The SW was excluded multivariable analysis with stepwise regression. In conclusion, the AV was influenced by both the AA and the VH. As the SW increases, the AA also tends to increase ($P < 0.001$), but it is more reasonable to determine the amount of augmentation using the AA than using the SW.

Based on these results, clinicians can obtain estimates of the required bone graft volume by measuring the AA before maxillary sinus augmentation. For example, assuming that sinus augmentation without simultaneous implantation is intended at a height of 9 mm and the AA is 40°, the AV regression model is as follows: AV = −1.267 + 0.23 × VH +

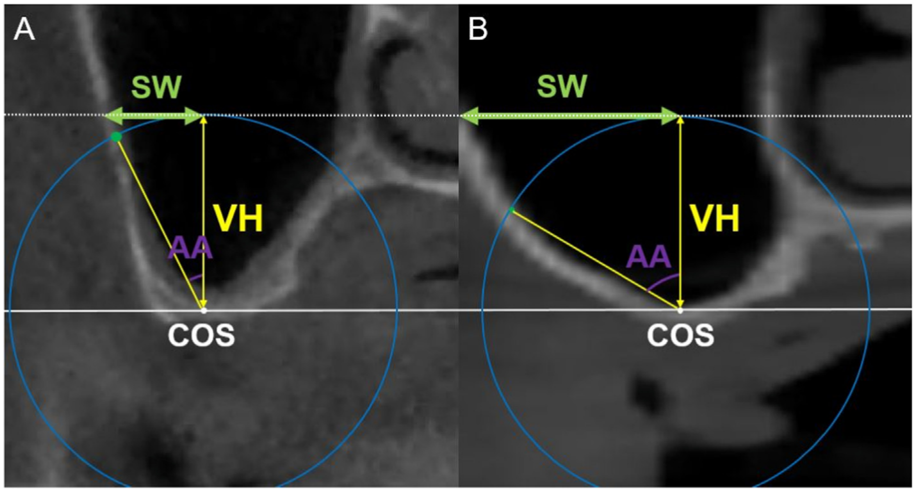

Figure 4 Correlation between the maxillary sinus width (SW) and augmentation angle (AA). As the SW increased, the AA also tended to increase. COS, center of the spherical; VH, vertical height.

Table 5 Univariable analysis of factors associated with AV in Group A and B (N = 120).

	Outcome variable	Predictor variables	*B*	*SE*	*B*	*P*-value
Group A	AV	SW	0.168	0.011	0.816	<0.001‡
	AV	AA	−0.026	0.003	−0.629	<0.001‡
	AV	VH	0.201	0.007	0.938	<0.001‡
Group B	AV	SW	0.168	0.011	0.815	<0.001‡
	AV	AA	−0.026	0.003	−0.625	<0.001‡
	AV	VH	0.202	0.007	0.931	<0.001‡

AV, augmentation volume; SW, sinus width; AA, augmentation angle; VH, vertical height; *B*, unstandardized coefficient; *SE*, standard error of coefficient; *β*, standardized coefficient.
‡*P* < 0.001.

0.007 × AA. Therefore, approximately 1.083 cc of bone graft material is required.

A previous study of 3D measurements predicted the required bone volume for sinus augmentation at heights of 15 and 20 mm in the maxillary molar area.[4] The results indicated that 4.02 ± 1.44 and 6.19 ± 1.77 cm^3 of bone grafting material was needed at heights of 15 and 20 mm, respectively. In another study, a bone volume of 1.7 ± 0.9 cm^3 was required for sinus augmentation with a height of 12 mm, and there was a correlation between the height of bone grafting and the amount of bone grafting.[6] Another analysis showed that the bone volume required for a 13.4 mm high sinus augmentation was 2.61 ± 0.69 cm^3 (1.38—4.1 cm^3) for the right maxillary sinus and 2.68 ± 0.81 cm^3 (1.1—4.25 cm^3) for the left maxillary sinus.[15] A difference between these studies and our study is that the previous studies measured the volume of the entire sinus region below a certain height. In reality, sinus augmentation is performed close to a dome-shape; therefore, our results are more relevant to clinical practice. In addition, we also analyzed the influence of the maxillary sinus augmentation angle and implant placement on the bone graft volume, which has not been previously studied.

A limitation of this study is that the simulation model only included a single implant placement and thus the findings may not be readily applicable to patients who receive multiple implants. However, our results could serve as a reference to determine the amount of bone grafting when placing multiple implants.

This study confirmed that the AV was significantly influenced by the AA and VH. Using a predictive model generated using linear regression, clinicians can predict the

Table 6 Multivariable analysis of factors associated with AV in Group A and B (N = 120).

	Outcome variable	Adjusted R^2	Predictor variables	*B*	*SE*	*β*	*P*-value
Group A	AV	0.891	(Constant)	−1.267	0.170		<0.001‡
			VH	0.230	0.010	1.067	<0.001‡
			AA	0.007	0.002	0.172	<0.001‡
Group B	AV	0.877	(Constant)	−1.283	0.181		<0.001‡
			VH	0.229	0.011	1.057	<0.001‡
			AA	0.007	0.002	0.168	0.001†

AV, augmentation volume; VH, vertical height; AA, augmentation angle; *B*, unstandardized coefficient; *SE*, standard error of coefficient; *β*, standardized coefficient.
†*P* < 0.01.
‡*P* < 0.001.

amount of bone grafting required for maxillary sinus augmentation with or without simultaneous implantation.

Declaration of competing interest

The authors have no conflict of interest relevant to this article.

Acknowledgments

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