Measurement of Maxillary Sinus Volume Using Computerized Tomographic Images

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This study measured maxillary sinus volume as an aid in determining the volume of graft bone needed before grafting autogenous bone to the maxillary sinus floor. Maxillary sinus volumes were measured from computerized tomographic images of 38 sinuses using a 3-dimensional reconstruction system. When the sinus-lift procedure was simulated, volumes (mean ± SD) of the inferior portion of the sinuses were 4.02 ± 1.44 cm^3 for 15-mm lifting and 6.19 ± 1.77 cm^3 for 20-mm lifting. In bone grafting of the maxillary sinus floor, taking into consideration individual differences in maxillary sinus volume and resorption of the grafted bone, 5.46 cm^3 or more were required for a 15-mm lift and 7.96 cm^3 or more were required for a 20-mm lift.
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Key words: bone grafting, computerized tomographic image, maxillary sinus floor, maxillary sinus volume, simulation

The placement of endosseous implants may be difficult in an edentulous posterior maxilla with a severely atrophic posterior or increased sinus pneumatization. Bone grafting to the maxillary sinus floor superiorly can increase the bone height of the posterior maxilla and enable the placement of such implants.[1–7] Grafting procedures have employed allografts, xenografts, and alloplastic materials.[8–11] Kirker-Head et al[12] reported a novel animal model of the maxillary sinus floor augmentation procedure used to assess bone formation in response to a recombinant human bone morphogenic protein-2 (rhBMP-2)/absorbable collagen sponge (ACS) sinus implant. However, BMPs are difficult to produce and are therefore extremely costly.

At present, an examination of the histologic data on bone formation and clinical success rates leaves little doubt that the ideal graft material for sinus-lift augmentation is autogenous bone.[13–17] For the autogenous donor site, the iliac crest or the mandibular symphyseal area are often used.[1–7,13,17] Estimating the bone volume to be harvested prior to surgery for maxillary sinus floor bone grafting might help in selecting the donor site, minimizing complications following bone harvesting, and reducing hospital expenses. Previous studies[2,5,6] have reported the volume of the graft bone used in the antral floor but have not described in detail the relationships between the height of sinus lifting and the graft bone volume required for the maxillary sinus floor. Recent developments in both computer and medical image processing technology have made possible the use of 3-dimensional reconstructed images of the skull generated from computerized tomographic (CT) images. These can assist the surgeon in determining the overall anatomical structure and measurements of maxillary sinus volume.[18]

The aim of the present study was to display a solid model of the maxillary sinus from CT images using a 3-dimensional reconstruction system and to measure sinus volumes for bone grafting in the maxillary sinus floor from the CT images.

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Materials and Methods

The study group comprised 11 male patients (18 sinuses) and 11 female patients (20 sinuses) ranging in age from 25 to 87 years. The patients were examined for maxillofacial disease (other than disease involving maxillary sinuses) at the Department of Oral and Maxillofacial Surgery, Saga Medical School, between 1981 and 1997. The maxillae of the patients were imaged on both axial CT and panoramic radiographs. All images included the maxillary sinuses, and all sinuses were asymptomatic and clearly free of any pathology such as fractures, inflammation, cysts, or tumors. Patients with clinical asymmetry or who had previously undergone surgical procedures were excluded from the study.

CT scanning was performed from the alveolar process to the infraorbital margin using a TCT-900S CT scanner (Toshiba Medical, Tokyo, Japan). The scan parameters were 120 kVp, 140 mA, and 1-mm contiguous slices. CT slices were obtained parallel to the Frankfurt plane. Panoramic radiographs were acquired using an Orthophos (Siemens AG, Erlagen, Germany), which was operated at 55 to 85 kVp (depending on the patient's anatomy) and 15 mA with an exposure cycle of 15 seconds. The unit was set for equal magnification (×1.25) of the anterior and posterior maxillary regions. All patients were also carefully positioned with the Frankfurt plane parallel to the floor.

The maxillae, maxillary sinuses, and scales on CT images were used to create a 3-dimensional image of the maxillary sinus, to display a solid model of each maxillary sinus, and to measure maxillary sinus volumes using the 3-dimensional reconstruction system.[19] The maxillae, maxillary sinuses, and scales on CT images were entered into an image-frame memory (Nexus 6800, Kashiwagi Research, Tokyo, Japan) from a XC-007 CCD color camera (Sony, Tokyo, Japan) with a FUJINON-TU•Z lens (Fuji Photo Optical, Tokyo, Japan) and displayed on a Sony Trinitron color video monitor PVM-1444Q (Sony, Tokyo, Japan). The contours of the maxillae and maxillary sinuses were digitized by tracing images with a crosshair pointer by advancing the cursor along the outlines seen in the images displayed on the monitor. Data were then sent to a minicomputer (Sun 4, Sun Microsystems, Mountain View, CA) where TRI software (Ratoc System Engineering, Tokyo, Japan) reconstructed a 3-dimensional structure. The scales on the CT images were used for coordinates and for calibration (units set to mm) for each section before the data for the contours of the maxillae and the maxillary sinuses were entered into the computer. The computer stored the X and Y coordinates as a sequence of points along the traced outlines. The vertical distance between each section, which was the same as the CT slice thickness (1 mm), provided the Z coordinate. Each serial section was successively entered from the alveolar process to the infraorbital margin at the same pitch. Wireframe images were generated from the stored data, and the sections were stacked by slice thickness. Wireframes corresponding to the same structures on serial upper and lower sections were connected with each other. A 3-dimensional reconstruction image was created by generating surfaces from the wireframes connecting the sections. The surfaces of the wireframes in each section were produced using triangular patches.[20] The final image, produced by hidden surface removal and shading, was displayed on a full-color graphic display monitor (GR4416, Seiko Electronics, Tokyo, Japan).

Maxillary sinus volumes were calculated on a Sun 4 minicomputer with TRI software. The volume of each section was $dV = dS \times \Delta h$ as shown in Fig 1a, where dS is the area of the maxillary sinus in a given section and Δh is the slice thickness of the section. Hence, the volume (V) of the region from the antral floor to a height of n mm was calculated as the sum of the volumes of each section (dV), that is, according to the formula:

$$V = \sum_{i=1}^{n} dS \times \Delta h \text{ (Fig 1a)}$$

Sinus volumes in which sections were stacked up from the antral floor to heights of 5 mm, 10 mm, 15 mm, and 20 mm, were calculated as described above (Fig 1b). These corresponded to a surgical simulation of bone grafting in the maxillary sinus floor, with lifting in increments of 5 mm from the antral floor up to 20 mm (Fig 1c). Total maxillary sinus volumes, in which the sections were stacked up from the antral floor to the top of the antrum, were also computed as described above.

The reproducibility and accuracy of measurements were assessed by comparing them with measurements taken from the head of a cadaver obtained from the collection of the Department of Anatomy, Saga Medical School. CT images of the specimen were obtained, and the bilateral volumes of the inferior portions of the sinuses (ie, the cavities from the antral floor to 5-mm lifting, 10-mm lifting, 15-mm lifting, and 20-mm lifting) and maxillary sinus volumes on both sides were measured using the same method as described above. The same cadaver head was scanned again 1 week later, and the same volumes were measured from the second set of CT images. With regard

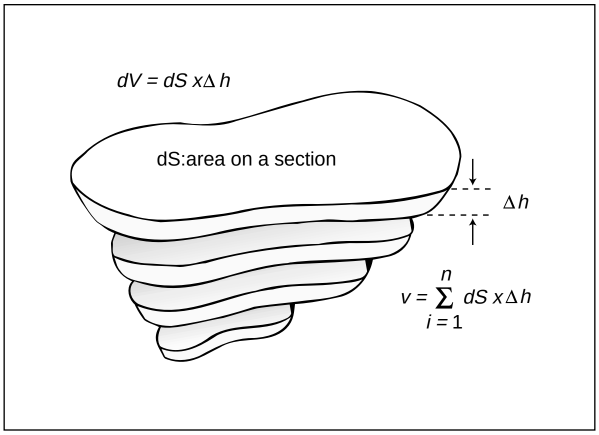

Fig 1a Diagram showing the method used in this study for measuring maxillary sinus volume using CT images.

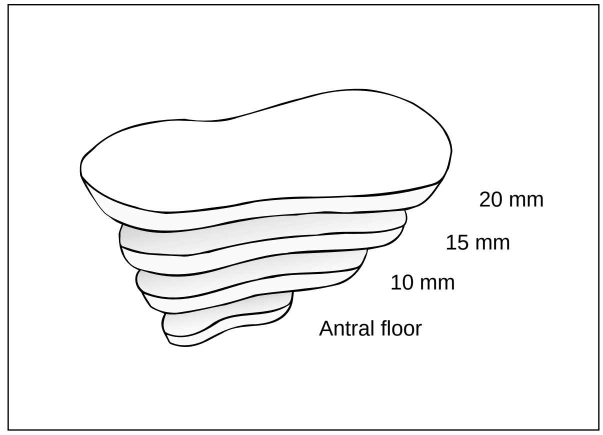

Fig 1b Inferior sinus volume measured by overlapping serial CT images from the antral floor when bone grafting in the maxillary sinus floor was simulated and the sinus floor was lifted in increments of 5 mm.

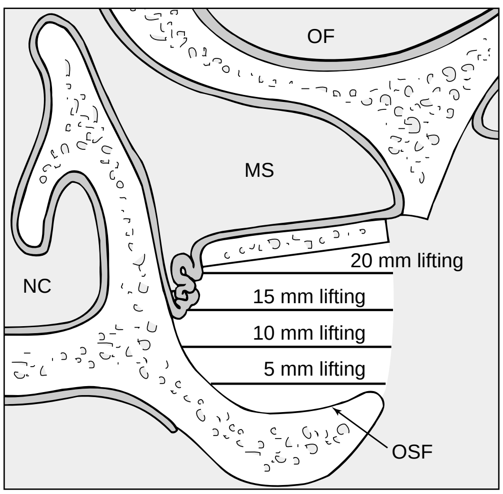

Fig 1c Schema for bone grafting in the maxillary sinus floor with lifting in increments of 5 mm from the antral floor up to 20 mm as surgical simulation (NC = nasal cavity, MS = maxillary sinus, OSF = original sinus floor, OF = orbital floor).

to reproducibility, measurement errors, which were assessed by differences between corresponding variables, were calculated as s(i) values.

$$s(i) = \sqrt{\frac{\Sigma(X_A - X_B)^2}{2N}}$$

With regard to accuracy, the bilateral maxillary sinus volume measurements obtained from CT images and maxillary sinus casts produced from dental impression material (Duplicone, Shofu, Kyoto, Japan) from the same cadaver were compared. Small holes were drilled in the canine fossae of the cadaver. The bilateral maxillary sinuses of the specimen were filled with the impression material using a syringe (Terumo, Tokyo, Japan). After the material had hardened, accurate solid casts of the sinuses were obtained. The casts were immersed in a graduated cylinder (Iwaki Glass, Tokyo, Japan) filled with water. The volumes of the casts were measured 3 times and then averaged. The maxillary sinus volumes measured on the CT images were also calculated 3 times for the same specimen and then averaged. To determine the accuracy, the degree of error, defined as the mean percent difference between the maxillary sinus volumes measured from the casts and from CT images, was computed as s(j)%.

$$s(j) = \sqrt{\frac{\Sigma(X_A - X_B)^2}{2N}} \times 100$$

Results

Three-Dimensional Display of the Maxilla and Maxillary Sinus. A wireframe model of the maxilla and maxillary sinus is shown in Fig 2a. Surfaces generated from the wireframes were used to create a solid model (Fig 2b). The maxillary sinus within a transparent maxilla is shown in Fig 2b.

Inferior Sinus Volume and Maxillary Sinus Volume. When bone grafting in the maxillary sinus floor was simulated, the sinus volumes (mean ± SD) measured on CT images were 0.70 ± 0.47 cm^3 in 5-mm lifting, 1.92 ± 0.84 cm^3 in 10-mm lifting, 4.02 ± 1.44 cm^3 in 15-mm lifting, and 6.19 ± 1.77 cm^3 in 20-

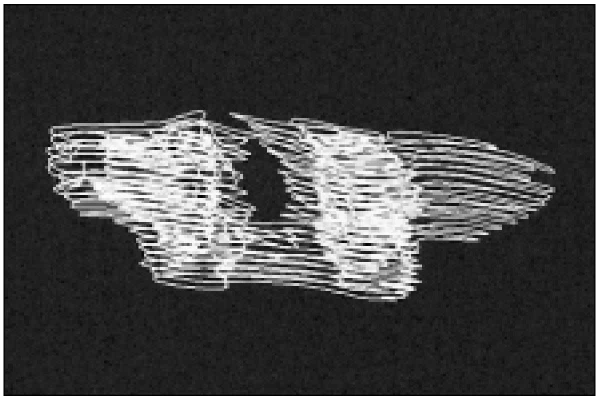

Fig 2a "Wire-frame" image of the maxilla and the maxillary sinus.

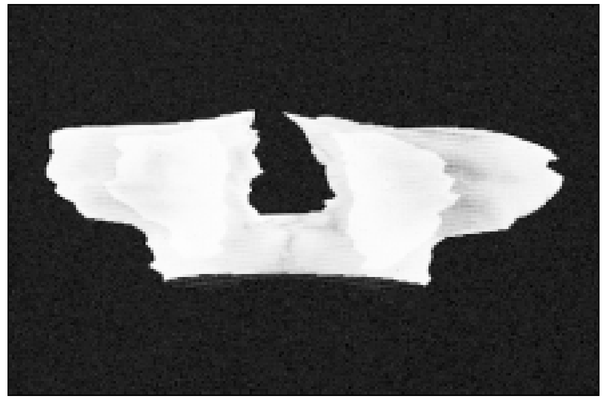

Fig 2b Three-dimensional reconstruction image obtained by generating surfaces from the "wire frames" among each section. The maxillary sinus in a transparent maxilla is shown.

Table 1 The Sinus Volume When Bone Grafting in the Maxillary Sinus Floor was Simulated and the Sinus Floor was Lifted in Increments of 5 mm (n = 38)

Amount of lifting	Sinus volume (cm^3; mean ± SD)
5 mm	0.70 ± 0.47
10 mm	1.92 ± 0.84
15 mm	4.02 ± 1.44
20 mm	6.19 ± 1.77

mm lifting (Table 1). The total maxillary sinus volume (mean ± SD) measured on CT images was 13.6 ± 6.42 cm^3. The minimum maxillary sinus volume was 3.5 cm^3 and the maximum was 31.8 cm^3.

Reproducibility and Accuracy of Measurement. Calculated error values were 0.03 cm^3 in 5-mm lifting, 0.07 cm^3 in 10-mm lifting, 0.11 cm^3 in 15-mm lifting, 0.12 cm^3 in 20-mm lifting, and 0.15 cm^3 for total sinus volume. The mean percent difference between the volumes of the bilateral maxillary sinus casts produced using dental impression material and the bilateral maxillary sinus volumes measured from CT images in the same cadaver was 5% or less.

Case Report. A 35-year-old Japanese female presented with an edentulous right posterior maxilla and a desire for implants and fixed prostheses. However, because of bone loss and increased antral pneumatization, residual bone height was 5 mm or less on a panoramic radiograph and there was inadequate bone mass for implant placement (Fig 3a). The patient was therefore considered a candidate for bone grafting in the maxillary sinus floor. To place an implant 13 mm or longer with reasonable expectation of a good clinical outcome, elevation of the maxillary sinus floor by 20 mm was deemed necessary. When the procedure was simulated for a 20-mm elevation of the right maxillary sinus floor, the required volume for the inferior portion of the sinus (mean ± SD) was 6.19 ± 1.77 cm^3 based on the data in this study (Table 1). Moreover, taking into consideration individual differences in maxillary sinus volume and resorption of the grafted bone, 7.96 cm^3 (adding the maximum standard deviation value to the mean value) or more was required for a 20-mm lift. Therefore, approximately 8 cm^3 of autogenous cancellous chip bone was harvested from the right ilium under general anesthesia. Bone grafting in the maxillary sinus floor was performed by the sinus augmentation procedure, with infracturing of the lateral maxillary wall. The maxillary sinus floor was raised 20 mm or more, and the recipient space was filled with the previously harvested cancellous iliac bone. A panoramic radiograph obtained 3 months after grafting showed that the minimum bone height between the alveolar ridge and the sinus floor was 23.3 mm (Fig 3b). A panoramic radiograph obtained 1 year after grafting showed that the sinus floor line had dropped because of resorption of the grafted bone (Fig 3c). The minimum bone height between the alveolar ridge and the sinus floor was 16.2 mm.

A 10 × 10-mm lead scale was attached to the panoramic radiographs of the patient. The minimum linear bone height from the alveolar ridge to the maxillary sinus floor on the panoramic radiographs was measured using a digital sliding caliper (Mitutoyo, Tokyo, Japan). Since the panoramic radiographs were magnified, the actual measurements were obtained by multiplying the measured values by the magnification ratio, which was determined from the scale included in the panoramic radiograph.

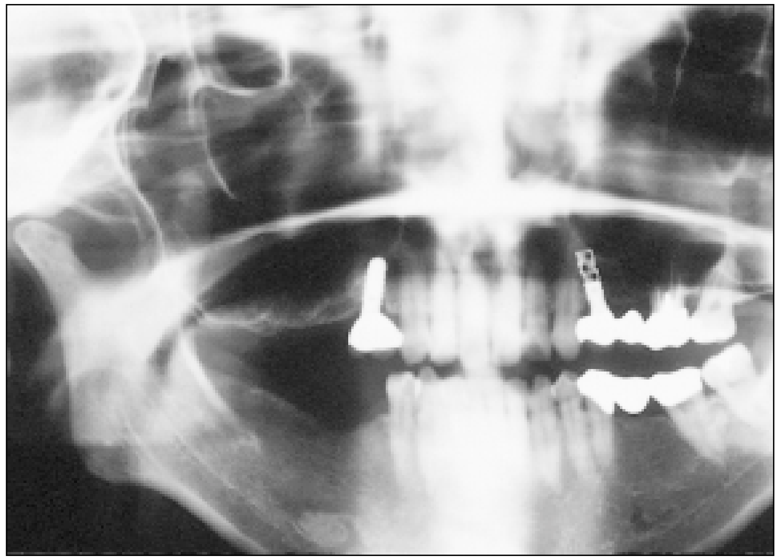

Fig 3a Preoperative radiograph of bone grafting in the maxillary sinus floor.

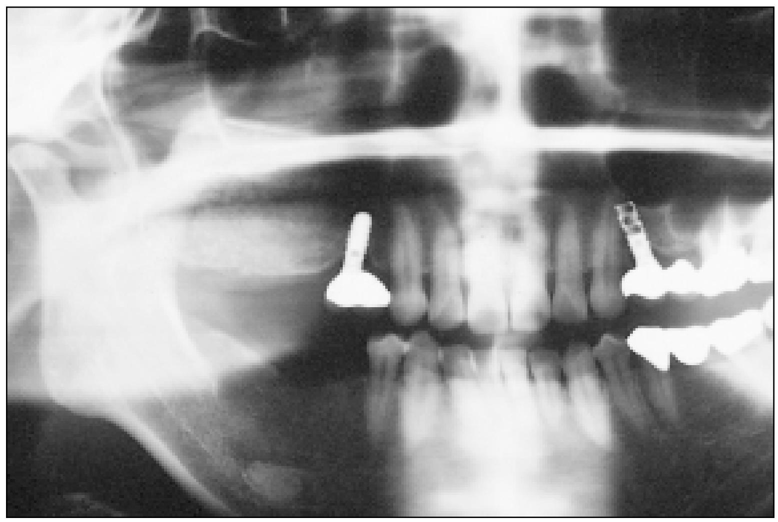

Fig 3b Postoperative radiograph of bone grafting in the maxillary sinus floor (3-month follow-up).

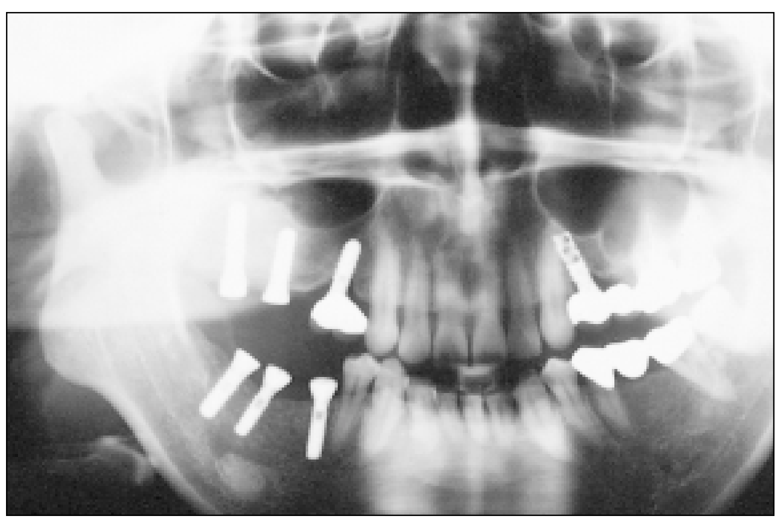

Fig 3c Postoperative radiograph of bone grafting in the maxillary sinus floor (1-year follow-up).

Table 2 Reported Donor Site, Grafting Bone Volume, and Implant Length in Conjunction with Maxillary Sinus Augmentation

Authors	Donor	Grafting bone volume	Implant length
Kent and Block[2] (1989)	Ilium	10 to 15 cm^3	13 or 15 mm
Keller et al[5] (1994)	Ilium	2 to 7.8 cm^3	15 or 18 mm
Isaksson[6] (1994)	Ilium	4 cm^3	10 to 18 mm

Discussion

The results of recent clinical and histologic studies indicate that autogenous bone is superior to any other grafting material[13–17] for elevation of the maxillary sinus floor and the placement of implants. At Saga Medical School, only autogenous bone is used in such situations. Accordingly, the present study was carried out based on the premise that only autogenous bone would be grafted to the maxillary sinus floor. Since autogenous bone must be harvested from the patient, determining the bone grafting volume prior to surgery is helpful in selecting the donor site for harvesting, in minimizing complications following the procedure, and in reducing medical expenses. For these reasons, preoperative measurement of the maxillary sinus volume is desirable so that the oral and maxillofacial surgeon can determine the amount of autogenous bone to be harvested from the donor site. The total volume of the maxillary sinus has previously been measured in human cadavers, with measurements obtained by injecting dental impression material into the maxillary sinus of the specimens.[21–23] In living subjects, Ariji et al[18] have reported maxillary sinus volume measured on CT images. Their method was similar to that used in the present study.

The CT images used for measurements in the present study included the maxillary sinus and were obtained for the evaluation of patients with other medical conditions in whom no abnormalities of the maxillary sinus were detected. Thus, CT was not specially performed to obtain images for sinus volume measurement in patients who underwent bone grafting in the maxillary sinus floor. Instead, with the objective of reducing examination costs, the mean and standard deviation values of the inferior maxillary sinus floor obtained in this study were employed for the benefit of patients who underwent bone grafting in the maxillary sinus floor.

SIM/Plant (Columbia Scientific, Columbia, MD), first introduced in 1993, was developed as preoperative planning software that combined the accuracy of CT imaging with the power of computer aided design.[24] Maxillary sinus volume measurement is possible using this software. However, at present, CT data acquired using our Toshiba CT scanner cannot be converted to the SIM/Plant format for input to a dedicated computer. The existing system does not depend on the CT data format; therefore, 3-dimensional reconstruction and measurement of CT data in various formats are possible.

Regarding method reproducibility, the measurement error for all volumes was 10% or less of the standard deviation (Table 1). There was no significant difference between the maxillary sinus volume measured from CT images of a cadaver and the volume of impression material injected into the maxillary sinus of the same specimen. The present method for obtaining measurements from CT images is therefore considered to be reliable and accurate.

Several investigators[2,5,6] have previously reported on the donor site, graft bone volume, and implant length in conjunction with bone grafting in the maxillary sinus floor (Table 2). The graft bone volume in these studies ranged from 2 cm^3 to 15 cm^3. However, none of these investigators detailed definite techniques of determining the graft bone volume. In surgical simulation in the present study, when bone grafting in the maxillary sinus floor was planned, the mean volume for bone grafting was 0.70 cm^3 for 5-mm lifting, 1.92 cm^3 for 10-mm lifting, 4.02 cm^3 for 15-mm lifting, and 6.19 cm^3 for 20-mm lifting (Table 1).

The lengths of implants that were placed in the grafted bone in the sinus floor ranged from 10 mm to 18 mm, as shown in Table 2.[2,5,6] After bone grafting in the maxillary sinus floor is performed, the length and number of implants placed in the graft bone are even more important factors in achieving long-term success.[25,26] Keller et al[5] routinely placed 3 Brånemark implants (Nobel Biocare AB, Göteborg, Sweden) 3.75 mm in diameter and 15 or 18 mm in length in each antrum. Li et al[7] also discussed the length and number of implants as follows: in the maxilla, a minimum of 6 implants measuring at least 13 to 15 mm in length were usually used for an implant-supported, fixed-removable prosthesis. If a fixed prosthesis was planned, a minimum of 8 implants would be needed to distribute the load.

The surface area of a maxillary premolar root is generally equal to the surface area of a 3.75-mm diameter Brånemark implant 13 mm or more in length. The surface area of a maxillary second molar root nearly matches the surface area of an implant 3.75 mm in diameter and 18 or 20 mm in length. The surface area of a maxillary first molar root is greater than the surface area of an implant 3.75 mm in diameter and 20 mm in length.[27] It has been suggested that the implant (3.75 mm in diameter) to be placed in the posterior maxilla should be 13 mm or more in length to achieve long-term success.[15]

In the present patient report, since implants of 13 mm or more in length were also placed in the posterior maxilla, the maxillary sinus floor required 20 mm of elevation. Then, taking into consideration these data (Table 1) and the resorption of grafted bone in the maxillary sinus floor, a volume of iliac cancellous bone chips somewhat greater than 7.96 cm^3 (adding the maximum standard deviation value to the mean value) was harvested. In a comparison of intraoperative findings and panoramic radiographs obtained 3 months after surgery, the maxillary sinus floor was elevated by approximately 20 mm, as estimated preoperatively. This demonstrates that the measurement results obtained in the current investigation were appropriate. However, although resorption of grated bone in the maxillary sinus floor was accounted for, a postoperative radiograph obtained at the 1-year follow-up examination showed that bone resorption of 7.1 mm had occurred and the minimum bone height could not be maintained at 20 mm or more. Thus, significant resorption of grafted bone occurred between 3 to 12 months. Postoperative resorption of grafted bone in the maxillary sinus floor has also been reported in the literature.[6]

Assuming that Brånemark implants 3.75 mm in diameter and 13 mm or more in length are to be placed in a severely atrophic posterior maxilla with a bone height of 5 mm or less, the maxillary sinus floor must be elevated 15 mm or more to achieve long-term success, taking into consideration the resorption of grafted bone in the maxillary sinus floor that occurred in this patient. From the present results, when bone grafting in the maxillary sinus floor was planned, the mean desired volume for bone grafting was 4.02 cm^3 for 15-mm lifting and 6.19 cm^3 for 20-mm lifting (Table 1). To lift the maxillary sinus floor 15 mm or 20 mm, at least 5.46 cm^3 or 7.96 cm^3 of bone, respectively, would be required for grafting in the maxillary sinus floor (adding the maximum standard deviation value to the mean value), considering individual variation in maxillary sinus volume and the resorption of grafted bone.

Extraoral sites for harvesting graft bone include the ilium and the cranium.[1–7] Intraoral sites include the ascending ramus, coronoid process, mandibular symphyseal region, and the maxillary tuberosity.[28–30] When grafting of the maxillary sinus floor with autogenous bone harvested from intraoral sites is performed, the drawback is that potential bone volume for harvest is limited.[31] For example, the graft bone volume that can be harvested from the mandibular symphyseal region ranges from 3 cm^3 to a maximum of 4 cm^3.[30] Based on the volumes of the inferior portion of the sinuses measured in the present study, at least 5.46 cm^3 or 7.96 cm^3 of bone is required for sufficient grafting in the maxillary sinus floor to obtain 15-mm lifting or 20-mm lifting, respectively. The morbidity associated with grafting from the anterior ilium is minimal compared with other extraoral donor sites, and it is possible to harvest a large amount of graft bone from the ilium. Hall et al[32] reported that the average intracortical volume of surgically accessible marrow space was 15.75 cm^3 for the anterior and 39.24 cm^3 for the posterior ilium. This result confirms the greater applicability of grafting with autogenous iliac crest bone. Moreover, many authors[1–7] have selected the ilium as the donor site since it is possible to harvest a large volume of graft bone there.

Conclusion

In the present study involving one patient, when bone grafting in the maxillary sinus floor was planned as surgical simulation, the volumes (mean ± SD) of the inferior portions of the sinus measured on CT images were 4.02 ± 1.44 cm^3 for 15-mm lifting and 6.19 ± 1.77 cm^3 for 20-mm lifting. Based on our findings, it can be concluded that a minimum of 5.46 cm^3 or 7.96 cm^3 of iliac crest bone is required for grafting to the maxillary sinus floor (adding the maximum standard deviation value to the mean value) to obtain 15-mm lifting or 20-mm lifting, respectively, taking into account individual variation in maxillary sinus volume and the resorption of grafted bone in the present case. The preoperative measurement of maxillary sinus volume in situations where autogenous bone grafting is to be incorporated into the treatment plan involving implant placement may be of assistance in determining the donor site. Its use as a routine procedure may not be practical.

Acknowledgments

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