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I. 서론

피질골이 얇고 해면골로 구성된 골밀도가 낮은 상악 구치부에서, 특히 상악동저까지 잔존골의 높이가 부족한 경우 임플란트 초기 안정성의 확보가 어렵고 장기적인 임플란트 성공률도 낮다. 잔존골이 부족한 저밀도의 상악 구치부에 임플란트 식립시 발생하는 한계를 극복하기 위해 다양한 상악동 거상술 기법이 고안되었다. 본 연구의 목적은 상악동 거상술을 위한 다양한 치조정 접근법을 시행하여, 정량적인 골침착량의 분석, 주변골의 치밀화 효과 평가, 골밀도에 따른 차이점 및 임플란트 일차 안정성을 비교하여 가장 효과적인 방법을 평가하는 것이다.

II. 재료 및 방법

신선한 24개의 돼지 상악동 및 11개의 돼지 흉골을 준비하였다. 그룹은 반시계방향 및 시계방향 골치밀화 드릴링, osteotome, crestal approach system kit, conventional drilling을 이용하여 치조정 접근방식의 상악동 거상술을 시행하였다.

상악동 막과 상악동 기저부 사이에 침착된 자가골을 micro CT를 이용하여 부피 변화를 평가하였고, HU 차이를 측정하여 hole 주변의 골치밀화 정도를 비교 평가하였다.

또한, 골밀도 차이에 따른 치밀화 효과를 비교하기위해, 상악골과 흉골에 드릴링을 시행하여 HU 차이를 비교하였다.

골밀도가 낮은 돼지 흉골에 같은 방식의 드릴링을 시행하여 임플란트 식립 후 Osstell Mentor®로 임플란트 안정성 계수(implant stability quotient; ISQ)를 측정하여 임플란트 초기 안정성을 평가하였다.

III. 결과

모든 그룹에서 상악동 막 천공이 발생하지 않았고, 반시계 방향의 골치밀화 드릴링에서 유일하게 상악동 막과 상악동 기저부 사이에 자가골 침착이 관찰되었다. 드릴 직경 증가시 평균 골침착량 변화는 작은 직경에서보다 큰 직경에서 증가폭이 컸다. 잔존골 높이 증가에 따른 평균 골침착량 변화는 잔존골의 높이가 낮은 경우에 높은 경우보다 증가폭이 컸다.

반시계 방향의 골치밀화 드릴링 시 가장 높은 HU 차이 값이 관찰되었고, 통계학적으로 유의한 차이가 존재했다. Osteotome 그룹은 다른 그룹에 비해 높은 HU 차이 값을 보였으나, 통계학적으로 유의한 차이는 없었다.

골치밀화 효과는 상대적으로 낮은 밀도의 흉골에서 높은 밀도의 상악골보다 유의하게 높은 값을 보였다.

반시계 방향의 골치밀화 드릴링 그룹에서 가장 높은 ISQ 값이 측정되었다. 골치밀화 드릴을 사용한 그룹에서 다른 그룹에 비해 높은 ISQ 값을 보였다.

IV. 결론

반시계방향의 골치밀화 드릴링은 잔존골이 부족한 저밀도의 상악 구치부에 임플란트 식립시 골밀도를 증가시키는 골의 치밀화를 통해 임플란트 초기 안정성을 높일 뿐 아니라, 상악동 거상술시 막을 천공시키지 않으면서 골의 침착을 유도하여 효과적인 상악동 거상술 기법이 될 수 있다.

Key words: Crestal Sinus Approach, Maxillary Sinus Augmentation, Autogenous Bone Deposition, Osseodensification, Implant Primary Stability

I. Introduction

Implant-supported prosthetic rehabilitation is predictable and has a high success rate.[1] The posterior maxilla is predominantly comprised of cancellous bone with a thin layer of cortical bone, resulting in low bone density. Further, alveolar bone resorption and sinus pneumatization after tooth extraction reduce the height and width of the residual bone.[2] These factors hinder the accomplishment of primary stability upon implant placement, leading to a relatively low success rate in the posterior maxilla.[3, 4] Maxillary sinus augmentation is often required prior to implant placement in the posterior maxilla, and therefore, safe and minimally invasive maxillary sinus augmentation techniques have been developed.

Maxillary sinus augmentation is broadly categorized into the crestal and lateral window approaches. The lateral window approach is advantageous with regard to directly viewing of the operative field, efficient bone grafting in cases requiring extensive augmentation, and immediate repair upon perforation of the sinus membrane. However, complications such as postoperative edema, hemorrhage, pain, and infection may arise due to an extensive flap or the creation of an additional surgical site. Moreover, the surgeon must have adequate clinical experience as the treatment may involve the posterior superior alveolar artery of the lateral wall and the septum in the maxillary sinus. This technique also has the drawback of a long operation time.[5] The crestal approach is relatively non-invasive with a lower frequency of perforation.[6] Nevertheless, there is a limit to the elevation of sinus membrane, and severe pneumatization may prevent its application in cases requiring extensive augmentation.

Various techniques and devices have been developed for the crestal approach technique. The current clinical practice employs the osteotome, reamer, or osseodensification drills. The osteotome technique exerts a compaction effect with simultaneous sinus membrane elevation and increased bone density at the surgical site.[7] A crestal approach system kit has also been developed; the kit comprises a unique, dome-shaped diamond drill that can help lift the sinus membrane without perforating it.[8] Osseodensification drilling is characterized by low plastic deformation of bone, where the sliding and rolling motions of the osseodensification bur in low-density bone result in a minimal thermal rise to increase the bone density. The sinus membrane is lifted through counter-clockwise rotations of the osseodensification bur with accumulation of the autogenous bone at the apex.[9]

Although the crestal approach technique has been studied extensively, no study has compared the types of the crestal approach technique in controlled experimental conditions. This study aimed to determine the most effective crestal approach technique for maxillary sinus augmentation based on the bone density, quantitative evaluation of bone augmentation, compaction effect on the surrounding bone, and primary stability of the implant.

II. Materials and Methods

Bone samples

Fresh samples from 12 one-year-old pigs were prepared. Twenty-four samples of the sinus were obtained from the maxilla on both sides (Figure 1). The thickness of the porcine maxillary sinus membrane is similar to that of the human maxillary sinus mucosa with adequate space for maxillary sinus for augmentation.[10, 11] In addition, for comparison based on the differences in bone density, 11 fresh porcine sternum samples were used. To reproduce the bone density of the human posterior maxilla, sternum samples of low bone density, composed solely of cancellous bone, were used.

Fig 1. Maxillary sinus augmentation with the crestal approach. (A) Porcine maxillary sinus, (B) Drilling for maxillary sinus augmentation, (C) Drilling in various diameters.

Experimental groups

The samples were divided into the following groups: osteotome group, which underwent the osteotome (Osstem Implant Co., Ltd., Seoul, Korea) technique; crestal approach system (CAS) group, which underwent reamer drilling with a CAS kit (Osstem Implant Co., Ltd., Seoul, Korea); and osseodensification group, which underwent osseodensification drilling in clockwise direction (OD-C) and counter-clockwise direction (OD-CC) with Densah bur (VT, Versah LLC, Jackson, MI, USA).

For the Implant Primary Stability (IPS) test, a group that underwent the following technique was also considered: conventional drilling (CD) with Osstem taper drill (Osstem

Implant CO., LTD., Seoul, Korea).

1. Evaluation of bone augmentation and densification

Following the conventional method, maxillary sinus augmentation was performed in the porcine maxilla. To minimize the error due to the drill diameter (as the drill diameter varies according to the manufacturer), the maximum error range was set to 0.2 mm based on the maximum drill diameter of ø 4.1 mm of the CAS kit. As a result, drilling was performed to ø 4.0 mm in the osteotome group, ø 4.1 mm in the CAS group, and ø 4.3 mm in the OD-C and OD-CC group.

To analyze bone augmentation and densification, micro-computed tomography (micro-CT; Quantum GX, PerkinElmer Inc., MA, USA) was taken for the samples. The micro-CT imaging conditions were set as follows: 4-minute exposure time, 45 mm field of view, 80 μA current, 90 kV voltage, and 90 μm voxel size. The micro-CT images were evaluated using the Quantum Image Viewer (Quantum GX SimpleViewer, PerkinElmer Inc., MA, USA) (Figure 2).

1) Evaluation of bone augmentation

The volume of the autogenous bone deposited between the maxillary sinus membrane and sinus floor was measured on the micro-CT images.

The effect of bone augmentation in OD-CC group was compared according to the drill diameter and residual bone height (RBH). To compare the bone augmentation volume according to the drilling diameter, the Densah bur was used for drilling at 1 mm intervals from 2.5 mm to 5.5 mm diameter. In addition, for the comparison according to RBH, the crestal bone in the porcine maxilla was removed to adjust the RBH to 2 mm intervals from 4 mm to 8 mm. As the sinus floor was not flat, the surgical site was adjusted to keep the error range below 1 mm. The sample size for bone augmentation test was 3 for each group (n=3).

2) Evaluation of bone densification

The Hounsfield unit (HU) values around the peri-implant drilling hole were measured to analyze the bone density. A 1 mm area around the implant drilling hole at 5 mm away from the apex was set as the region of interest (ROI) (Figure 3A and B). Within the ROI, the HU values at the highest and lowest points were measured, and the gap was analyzed (Figure 3B). The sample size for bone densification test was 4 for each group (n=4). The HU values were measured ten times, and the mean values were obtained. In addition, to compare the densification effect based on the variation in bone density, a Densah bur of 5.5 mm diameter was used to drill a hole in the maxilla and sternum samples, and using the same method, the HU values were measured and compared.

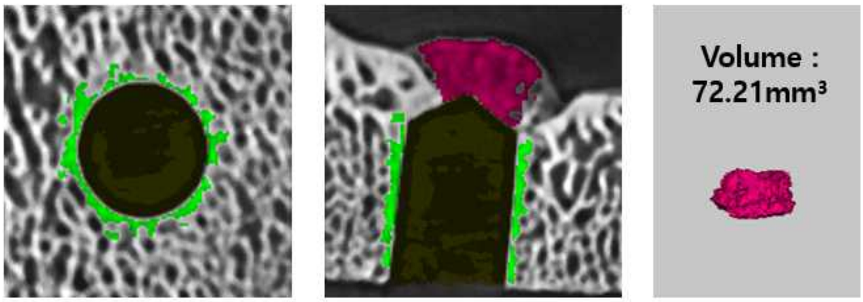

Fig 2. The volume of the deposited bone between the sinus membrane and the maxillary sinus floor after sinus augmentation was calculated using 3D Micro-CT.

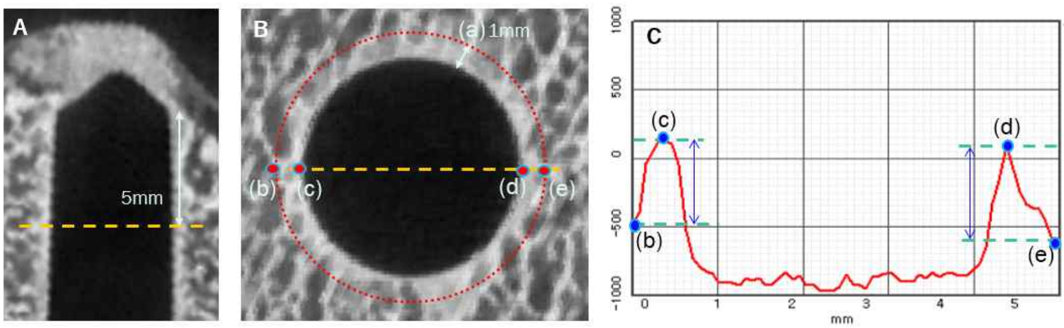

Fig. 3. The difference in the Hounsfield unit values at the highest and lowest points of the region of interest was measured. (A) the implant drilling hole at 5 mm away from the apex, (B, C) (a) 1 mm of ROI around the implant drilling hole, (b, e) the lowest point, (c, d) the highest point.

2. Implant primary stability test

To evaluate the IPS, low-density sternum which removed cortical bone was drilled based on the manufacturer's instructions up to ø 4.3 mm in the CD group, ø 4.0 mm in the osteotome group, ø 4.1 mm in the CAS group, and ø 4.3 mm in the OD-C and OD-CC group. A fixture of ø 4.5 mm and 10 mm length (TSIII SA, Osstem Implant CO., LTD., Seoul, Korea) was placed at 50 rotations/min and 50 Ncm. Using the Osstell^{TM} ISQ (OSSTELL, Göteborg, Sweden), a resonance frequency analysis was performed, and the implant stability quotient (ISQ) was measured four times for each implant. The sample size for implant primary stability test was 10 for each group (n=10).

Statistical analysis

Based on the normality of the bone augmentation data, one-way ANOVA was performed, followed by the Games-Howell post-hoc test. Based on the normality of the bone densification data, one-way ANOVA was performed, followed by the Tukey HSD post-hoc test. Due to the lack of normality in bone density variation between the maxilla and sternum and in the between-group variation in the ISQ, the Kruskal-Wallis test and Mann-Whitney test were applied. The significance was tested using SPSS 25.0 (IBM Crop., NY, USA) with the level of significance set to $p < 0.05$.

III. Results

Bone augmentation test

Bone augmentation between the sinus membrane and sinus floor was observed only in the OD-CC group (Figure 4D). The osteotome, CAS, and OD-C groups showed no deposition of autogenous bone (Figure 4A, B and C). Sinus membrane perforation did not occur in any group.

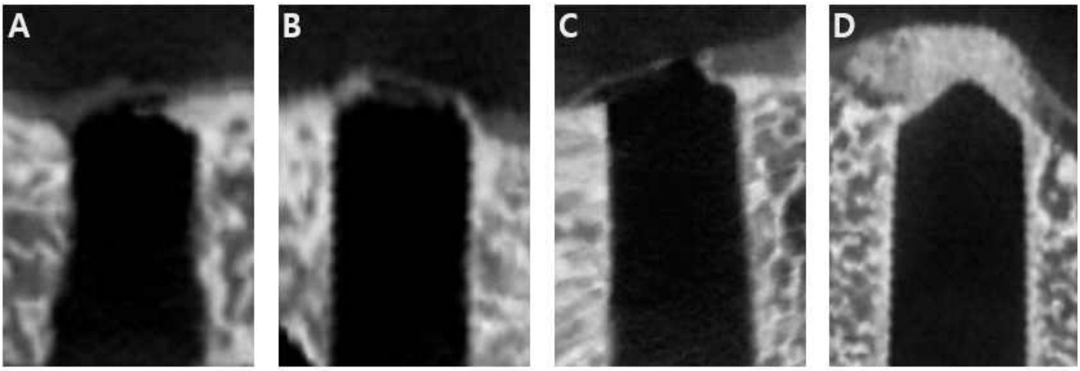

Fig 4. Micro-CT image after sinus augmentation using various crestal techniques. (A) osteotome technique group, (B) CAS kit group, (C) OD-C group, (D) OD-CC group.

Autogenous bone deposition was positively correlated with the drilling diameter and RBH, and the mean bone augmentation ranged between 0.81 ± 0.18 mm^3 and 57.43 ± 14.70 mm^3 (Table 1).

At the identical RBH and according to the drilling diameter, the mean bone augmentation was 18.01 mm^3, 115.74 mm^3, 209.04 mm^3, and 443.29 mm^3 at 1 mm intervals from ø 2.5 mm to ø 5.5 mm. No significant increase in mean bone augmentation was found as the drilling diameter increased from ø 2.5 mm to ø 3.5 mm (97.73 mm^3) and as it increased from ø 3.5 mm to ø 4.5 mm (93.3 mm^3). The increase was more than two-fold (233.89 mm^3) as the drilling diameter increased from ø 4.5 mm to ø 5.5 mm.

At the identical drilling diameter, the mean bone augmentation was 14.83 mm^3, 24.33 mm^3, and 26.34 mm^3 for an RBH 4 mm, 6 mm, and 8 mm, respectively. The increase in mean bone augmentation was greater for the increase in RBH from 4 mm to 6 mm (9.50 mm^3) than for the increase in RBH from 6 mm to 8 mm (2.01 mm^3).

Table 1. The volume of augmented bone between the maxillary sinus membrane and sinus floor according to the diameter of counter-clockwise osseodensification bur and residual bone height (n=3) (mean ± standard deviation, mm^3)

diameter / RBH	4 mm	6 mm	8 mm
2.5 mm	0.81 ± 0.18	2.56 ± 1.48	2.62 ± 2.30
3.5 mm	7.36 ± 3.48	15.14 ± 3.45	16.07 ± 5.80
4.5 mm	15.00 ± 4.15	25.44 ± 5.01	29.23 ± 10.38
5.5 mm	36.16 ± 1.97	54.16 ± 28.23	57.43 ± 14.70

RBH: Residual bone height.

Bone densification test

The greatest HU gap was observed in the OD-CC group (254.65 ± 125.98 HU) with significant variation from the other groups ($P < 0.05$) (Table 2). The lowest HU gap was observed in the OD-C group (125.75 ± 167.08 HU). The HU was greater in the osteotome group (164.00 ± 132.01 HU) than in the CAS or OD-C group but without a significant difference. The HU was greater in the CAS group (130.37 ± 130.77 HU) than in the OD-C but with no significant difference.

The mean HU gap for the porcine sternum with a relatively low bone density was 366.00 ± 24.06 HU, while that for the maxilla with a high bone density was 292.50 ± 39.51 HU, with a significant difference ($p = 0.043$) (Table 3 & Figure 5).

Table 2. Analysis of the difference between the highest and lowest HU values of the bones around the drilling hole in the porcine posterior maxilla (n=4)

Group	HU gap (Mean ± SD)	p-value
OD-CC	254.65 ± 125.98	-
OD-C	125.75 ± 167.08	0.000*
CAS	130.37 ± 130.77	0.001*
Osteotome	164.00 ± 132.01	0.022*

*Represents statistically significant difference between OD-CC groups ($p < 0.05$).

HU : Hounsfield unit, OD-CC: Osseodensification technique in the counter-clockwise direction group, OD-C: Osseodensification technique in the clockwise direction group, CAS: Using CAS kit group, Osteotome: Using Osteotome technique group.

Table 3. Analysis of differences in HU values according to bone density in porcine sternum and maxilla

	Sternum	Maxilla	P-value
HU gap (Mean ± SD)	366.00 ± 24.06	292.50 ± 39.51	0.043*

*Represents statistical significantly different between test group ($p < 0.05$)

OD-CC: Osseodensification technique in the counter-clockwise direction group, HU : Hounsfield unit.

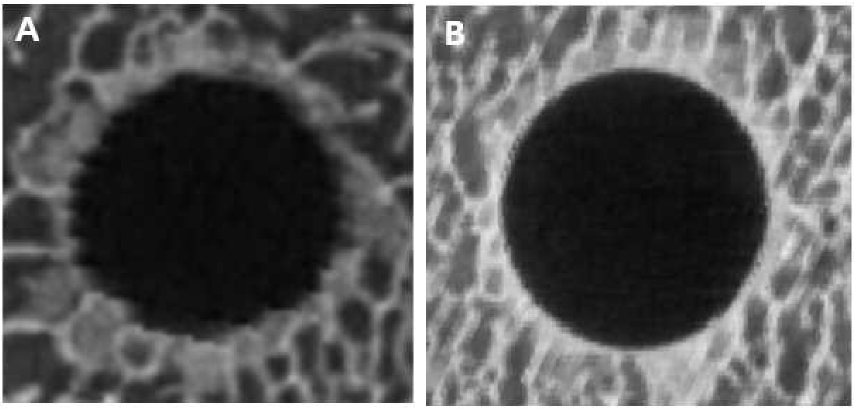

Fig. 5. Micro-computed tomography showing the difference in densification according to bone density. (A) Porcine sternum, (B) Porcine maxilla.

Implant primary stability test

The lowest ISQ was shown by the CD group (66.00 ± 2.19). The OD-CC group had the highest ISQ (70.10 ± 5.58), which was significantly different from the other groups ($p < 0.001$). The ISQ was higher for the OD-C and OD-CC groups, where the Densah bur was used, compared to the other groups. The ISQ was significantly higher for the CAS group (67.70 ± 2.01) than for the CD group ($p = 0.001$). The ISQ was higher for the osteotome group (66.97 ± 1.77) than for the CD group but without significant difference ($p = 0.159$) (Table 4).

Table 4. Implant primary stability evaluation (n=10) (Mean ± standard deviation)

	CD	Osteotome	CAS	OD-C	OD-CC
ISQ	66.00 ± 2.19	66.97 ± 1.77	67.70 ± 2.01	68.20 ± 3.43	70.10 ± 5.58
p-value (CD)	-	0.159	0.001*	0.003*	< 0.001*
p-value (OD-CC)	< 0.001***	< 0.001***	< 0.001***	< 0.001***	-

*Significant difference between the control groups ($p < 0.05$).

***Significant difference between the OD-CC groups ($p < 0.001$).

ISQ value: Implant stability quotient value, CD: Conventional technique group, Osteotome: Using Osteotome technique group, CAS: Using crestal approach system kit group, OD-C: Osseodensification technique in the clockwise direction group, OD-CC: Osseodensification technique in the counter-clockwise direction group.

IV. Discussion

Inadequate vertical bone height and low bone density between the sinus floor and alveolar ridge affects the implant primary stability and long-term success rate of implant placement in the edentulous posterior maxilla.[12] Lekholm and Zarb[13] classified bone density into four types based on the distribution and shape of the cortical and trabecular bone. In general, the posterior maxilla exhibits a low bone density of type III or IV.[14] In addition, the maxillary sinus shows gradual pneumatization and enlargement after tooth extraction in the posterior maxilla with resorption of the alveolar bone. This reduces the vertical dimension of the alveolar bone and acts as a limiting factor of implant placement.[5] To overcome these limitations, various techniques and methods of maxillary sinus augmentation have been developed.

The osteotome technique, first introduced by Summers in 1994, uses the crestal approach to induce an incomplete fracture of the sinus floor to augment the sinus membrane for the bone graft.[15] A previous study showed that bone grafting is not essential to maintain the augmented space for implant osseointegration.[16] In addition, the osteotome technique has been recommended for cases with a minimum of 5 mm residual bone height, while the risk of perforating the sinus membrane is greater when the residual bone height is less than 5 mm.[7, 17] Perforation may occur during mallet tapping using the osteotome, and shock-induced changes in an otolith may cause otolithiasis accompanied with nausea. To overcome these limitations, various methods such as the use of a specialized drill or hydraulic pressure have been developed. The modified osteotome technique introduced by Tatum involves a hydraulic system,[18] which lowers the risk of mucosal perforation by preventing direct contact with the device by lifting the sinus membrane using water pressure.[7, 19] However, its drawbacks include a prolonged operation time and difficulty in verifying the complete elevation of the maxillary sinus mucosa.[20]

The reamer technique was introduced as an alternative to the osteotome technique. The advantage of this technique is that a thin layer of bone is left on the sinus floor to prevent direct contact between the membrane and the reamer.[21] In addition, the device allows control of speed and shows an outstanding level of bone cutting so that it can be used even where the septum is present. The absence of tapping motion also allows decreased levels of discomfort and nausea.[22] The CAS kit, based on the principles of the reamer device, consists of a special drill with a conical shape and a unique design to prevent immediate perforation even upon a contact with the sinus membrane.[23] After the safe removal of the bone of the sinus floor, hydraulic pressure is used to lift the maxillary sinus mucosa.[24] The internal stopper varies in length to prevent over-drilling. In addition, an outstanding level of bone removal allows the device to be used even where the maxillary sinus septum is present or the sinus floor is tilted. Yassin reported that the use of the CAS kit enabled the augmentation of the maxillary sinus mucosa up to 5 mm without perforation.[24]

The recently introduced osseodensification drilling technique involves the counter-clockwise rotation of the densifying bur to generate fine bone particles, which are dispersed across the implant threads and surrounding bone marrow to increase the bone density in the vicinity of the implant.[25] The counter-clockwise rotation of the osseodensification bur exerts a compressive force on the bone surface under ultimate strength, while the preservation of a part of the autogenous bone graft leads to the compression of the bone around the peri-implant hole and deposition under the maxillary sinus mucosa to elevate it without penetration.[9] As a result, an implant longer than the vertically deficient bone height can be placed with implant primary stability. The manufacturer of the Densah bur reported that the device could be used without bone graft to lift the maxillary sinus mucosa to a height below 3 mm. Osseodensification maxillary sinus augmentation without bone graft had been reported in previous studies. Shereen W performed osseodensification maxillary sinus augmentation without bone graft in 12 randomly selected patients and reported gain in alveolar bone height by 3.33 ± 0.25 mm after six months.[26] In another study, the residual bone height was measured six months after the maxillary sinus augmentation using the osseodensification bur, and an increase from 4.18 ± 1.22 mm up to 13.58 ± 1.06 mm was reported with an increase in the IPS.[27]

In this study, porcine maxilla with a membrane thickness similar to that of the human sinus membrane was used, and to reproduce the low bone density of the human posterior maxilla, low-density porcine sternum without cortical bone was used. Various studies have pointed out the importance of the removal of cortical bone to ensure accurate evaluation of initial implant stability.[28] All groups that received the crestal approach for maxillary sinus augmentation showed no perforation of the sinus membrane, while the autogenous bone deposition was observed only in the osseodensification group, which underwent osseodensification drilling in clockwise direction. This indicates that, while the fine bone fragments are washed away during the general drilling process, they adhere across the flute during osseodensification drilling and are deposited as autogenous bone graft in the surrounding bone. In this study, likewise, the mean bone augmentation was 25.44 mm^3 upon the use of a ø 4.5 mm osseodensification bur when the residual bone height was approximately 6 mm. As the osseodensification bur diameter was increased at 1 mm intervals, the bone deposition was greater for larger diameters than for smaller diameters, which indicated a greater bone augmentation effect while placing implants of larger diameters. As the residual bone height was increased at 2 mm intervals, the increase in bone deposition was greater for lower residual bone height than for higher residual bone height. The results implied that, in identical conditions, the increase in diameter had a greater influence on bone deposition than did the residual bone height.

In the osteotome group, the compaction effect without a distinct effect on bone densification test was confirmed. In the OD-CC group, a high compaction effect was observed with increased density of the surrounding bone. The variation in densification was approximately 73 HU gap between the maxilla with high bone density (HU gap: 292.50 ± 39.51) and the sternum with relatively low bone density (HU gap: 366.00 ± 24.06), which indicated a greater effect on bone deposition in low density bone. In the case of posterior maxilla, compared to the mandibular bone, type III and IV are more frequent, implying a greater bone deposition effect of osseodensification drilling.

For the posterior maxilla with low bone density, IPS is a critical factor in osseointegration. Various methods are available to measure the IPS, including insertion torque, resonance frequency analysis, and Periotest, of which the implant insertion torque is the most accurate; however, due to the difficulty in using this method with a reliable accuracy in clinical practice, ISQ value was measured as an alternative. The ISQ is a useful predictor of the level of implant osseointegration, which shows a positive correlation with the implant insertion torque.[29] Thus, a high initial ISQ implies a high level of insertion torque.[30] The results presented in Table 4 may indicate the increase in implant initial stability through osseodensification drilling in low-density bones. The ISQ in this study was ø 4.3 mm for the Densah bur, ø 4.1 mm for the CAS kit, ø 4.0 mm for the osteotome, and ø 4.3 mm for the Osstem taper drill, i.e., the ISQ was significantly higher for the Densah bur with a larger diameter despite the low under-drilling effect. Thus, for the same diameter, the ISQ is predicted to be greater on using osseodensification bur.

This study was conducted *ex vivo*, and the resorption of the deposited autogenous bone could not be evaluated. Neither the effect on osseointegration nor the long-term implant stability could be assessed. These limitations should be addressed in an *in vivo* study or a long-term clinical study in future. Nevertheless, quantitative analyses performed in controlled conditions in this study, which are not possible in a clinical trial, led to the collection of objective data. All techniques were shown to ensure safe lifting without sinus membrane perforation, and notably, the osseodensification crestal approach can be an effective maxillary sinus augmentation technique due to autogenous bone deposition and compaction effects with high implant primary stability.

V. Conclusion

The osseodensification crestal approach can effectively augment the maxillary sinus through densification and autogenous bone deposition in cases of insufficient vertical alveolar bone with low-density.

1) Bone augmentation between the sinus membrane and floor was observed only in the OD-CC group. As the drilling diameter gradually increased, the amount of bone deposition also increased.

2) The OD-CC group showed the highest hounsfield unit gap. The hounsfield unit gap of the osteotome group was higher than that of the CAS group and the OD-C group, but there was no statistically significant difference. The hounsfield unit gap in the OD-CC group was significantly higher than that in the osteotome group.

3) The compaction effect was significantly higher in the low-density bone than in the high-density bone.

4) The OD-CC group showed the highest implant stability quotient. The OD-CC and OD-C groups showed statistically higher implant stability quotient values than those in other groups.

VI. References

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