Objective evaluation for Endoscopic Sinus Surgeries' proficiency by image analysis for postoperative 3D sinus models

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ABSTRACT

Objective:

Objective assessment for endoscopic sinus surgery skill proficiency is challenging, partly due to the great diversity of anatomies. Recently developed 3D-printed sinus models provide standardized anatomy with realistic tissue-feel. In this study, we developed a method to evaluate endoscopic sinus surgery skill proficiency through pre- and post-operative image analysis of CT images of dissected 3D sinus models and validated it by comparing to other surgical proficiency indices.

Methods:

Forty-seven otolaryngologists performed endoscopic sinus surgery for 3D sinus models. CT images of each postoperative 3D model were taken. The region growing method, an image segmentation technique, was utilized to assess the surgical space expansion. The region of interest (ROI) was defined as the space within nasal cavity and paranasal sinuses and continuous from the anterior nostril with a width of more than 4.00 mm kept. The volume of ROI was estimated and compared with conventional assessment methods such as board-certification, the objective structured assessment of technical skills score, and the number of experienced surgery cases. Further, the 3D-CG images of ROI were created. The completion of surgical steps within the allocated time was evaluated based on the 3D-CG and compared with the recorded endoscopic video.

Results:

The volume in postoperative models was 24.48±4.34 cm^3 across all participants, respectively. The postoperative volume was significantly larger in board-certified participants (certified; 25.51±4.22 cm^3 vs. uncertified; 22.87±4.14 cm^3, $p=0.03$). The volume is positively correlated to the objective structured assessment of technical skills score ($r=0.72$, $p<0.01$) and the number of experienced cases ($r=0.51$, $p=0.01$). The accuracy of the 3D-CG judgement for completion of a surgical middle meatal antrostomy, sphenoidotomy, and frontal sinusotomy were 91.3%, 69.6%, and 84.8%, when compared to recorded endoscopic video, with high sensitivity and specificity.

Conclusion:

The combination of standardized 3D models and image analysis provides a simple and objective tool for the assessment of surgical skill proficiency.

Key words: *ESS, 3D-printer, surgical education, chronic rhinosinusitis, 3D slicer*

INTRODUCTION

Endoscopic Sinus Surgery (ESS) is the standard of care for the management of chronic rhinosinusitis refractory to appropriate medical treatment [1]. ESS is performed to reduce the inflammatory burden and widen the sinus ostia to facilitate the ventilation, drainage and most importantly increase access to topical therapies. Compared to many other surgeries, ESS holds unique features, requiring delicate two-handed handling of an endoscope and surgical instruments in three-dimensionally complex paranasal sinuses viewed on a two-dimensionally monitor. This is not necessarily intuitive and not easy for residents to acquire the skills. Furthermore, the paranasal sinuses are directly adjacent to vital structures including the orbits and skull base, which associates the surgery with significant risk. These factors require residents to spend significant time and effort acquiring the competency of the surgeries, as a learning curve for acquiring ESS was reported [2]. The mainstream of ESS training has been on-the-job training in theatres, where registrars perform the surgeries under the supervision of the senior surgeon. This is inevitably associated with poorer outcomes from poor tissue handling and trauma to collateral structures as well as a higher rate of direct and indirect complications. With increasing social demand for patients' safety during surgical training and the work hour restriction in a residency program, ESS training ideally should be optimized, and the assessment for ESS skill proficiency is in demand.

So far, various ESS skill assessments have been proposed, including use of scoring systems [3] or motion analysis [4]. These have all assessed the surgical process in theatre, and none have assessed how the anatomy of paranasal sinuses has changed with surgeries. Considering the purpose of ESS to optimize the paranasal sinuses anatomy to regulate inflammation, the postoperative morphology of paranasal sinuses also should be assessed, as well as the surgical process. One of the reasons that such morphology-focused skill assessment has not been established is the great diversity of paranasal sinus anatomy. This inter-patient variability also makes it difficult to assess the acquisition of surgical skills amongst residents, as case difficulty cannot be standardized.

Recently developed advanced manufactured 3D printed sinus models, generated from high resolution computed tomography (CT) dicoms of actual patients undergoing surgery provides standardized anatomy with realistic tissue-feel. Such models and their CT scans are therefore well suited for standardized assessment of the acquisition of surgical skills [5].

In this study, we developed a method to evaluate ESS skill proficiency through pre and post-operative image analysis of the CT images of dissected 3D sinus models and discussed its feasibility and validity by comparing to other ESS proficiency indices.

MATERIALS AND METHODS

Participants

The institutional review board approved the present study (No. 018-043). This study was performed as a sub-analysis of the previously published study on the surgical training using 3D sinus models [6, 7]. A total of 47 otolaryngologists volunteered for this study. The purpose and design of the study was explained to the participants in advance, and written informed consent was obtained from all participants. The participant questionnaire collected information regarding participant age, sex, dominant hand, certification system status, years of experience as an otolaryngologist, and previous experience with ESS cases. The participants were categorized into two groups, board-certified or uncertified, based on their specialist status as defined by the certification system of the Japanese Society of Otolaryngology Head and Neck Surgery.

Simulation surgeries

The participants were allocated 45 minutes to perform ESS surgeries on the right paranasal sinus cavity of the 3D-printed sinus models (FuseTec, Adelaide, South Australia). The details of the surgical training process have been described in previous studies [6]. The models were 3D-printed from the CT scans of actual patients with chronic rhinosinusitis and validated for ESS training [6]. The right side of the model used in the study hold an Onodi cell without Haller cells, concha bullosa, nor septal deviation. The frontal sinus drainage pathway was surrounded by an agger nasi cell, a supra agger frontal cell, a bulla ethmoid, and a supra bulla cell. More details of anatomical characteristics are written in previous report [6]. The order that the surgical steps to be performed was standardized as follows.

Step 1: uncinectomy
Step 2: middle meatal antrostomy
Step 3: anterior ethmoidectomy
Step 4: posterior ethmoidectomy
Step 5: sphenoidotomy
Step 6: frontal sinusotomy

The details of the simulation surgeries were described in the previously published paper [6].

The surgical skills of the participants were assessed by an experienced rhinologist (MS) according to the Objective Structured Assessment of Technical Skills score of the ESS (ESS-OSATS) [3]. Another experienced rhinologist (YN) scored 24 randomly selected videos, and the results were evaluated by calculating the correlation coefficient and the intraclass correlation coefficient between the scores of the two rhinologists. Furthermore, videos of all surgeries were blindly scored for "progress status" defined as the number of the surgical steps that the participants had completed by the end of the allocated time. The detail of these assessment methods was described in the previous publications [6].

After the completion of all participants' surgeries, CT images of the postoperative 3D models were taken with a 16-slice multidetector-row CT scanner (Hitachi, Tokyo, Japan) with collimation of 0.63 mm at 120 kV and 200 mA or less and a rotation time of 1.0 sec.

Image analysis

To date, no method has been established for comparison of postoperative sinus morphology in three dimensions. This study focused on the volume of the nasal cavity and paranasal sinuses estimated by image analysis and compared that with other ESS proficiency indices (ESS-OSATS and previous experienced cases).

Image analysis software 3D Slicer [8] was used to estimate the volume. The region growing method was utilized to assess the surgical space expansion within the nasal cavity and paranasal sinuses. This method can segment areas or spaces contiguously from any arbitrary point. The region of interest (ROI) was defined as the space within nasal cavity and paranasal sinuses and continuous from the anterior nostril with a width of more than 4.00 mm kept. The width threshold was set for the analysis because all the sinuses even in preoperative condition are anatomically continuous to the anterior nostril through their own drainage pathways, even though some pathways are less than 1 mm. Therefore, without the threshold for the width, the ROI would always contain all the space within the sinuses, regardless of pre- and post-surgeries. Grobler et al. report that 3.95 mm is the minimum dimension to ensure penetration for maximum efficacy of topical sinus medications [9], and one of the major purposes of surgery is to improve their efficacy. Therefore, the threshold of 4.00 mm was chosen as the minimum value that can be set with the 3D Slicer above 3.95 mm.

A computed graphic (CG) model was created from the CT images and processed, and the volume of the ROI was measured according to the following procedure (Fig. 1.). First, a CG model of the paranasal sinus was constructed from the CT images (Fig. 1. A). The outer frames of the 3D models (the anterior nostril, the frontal sinus, and the maxillary sinus) was virtually blocked (Fig. 1. B). The walls of the nasal cavity were inflated by 2.00 mm prior to the region growing (Fig. 1. C). This means virtually blocking the passage below 4.00 mm and excluded the space more peripheral than the point. Then, region growing method was performed using the anterior nostril as a seed point to search for passages through to identify the ROI (Fig. 1. D). After the region growing was applied, the walls of the nasal cavity that had been inflated were deflated (Fig. 1. E) and the ROI was obtained by inflating the surface of the grown region by 2.00 mm (Fig. 1. F and G). The volume of the ROI was then measured (Fig. 1. H). Although Fig. 1. A-H show the sectional views on the representative plane (the sagittal plane) to show the measurement flow, the analysis was performed in 3-dimensional space containing the other axial and coronal planes.

The progress status of surgeries judged with 3D-CG

Based on the CG images of the ROI mentioned above (Fig. 2), it was judged by a rhinologist whether the ROI reached to the maxillary, sphenoid, and frontal sinuses, respectively. The progress status based on CG images were compared to those on the recorded videos. In the video-based assessment, each surgical step was judged as achieved if the ostium of each sinus was widened regardless of the size of them.

Statistical analysis

Aggregated data were presented in the results in the form of mean ± standard deviation. The Shapiro-Wilk test was applied to examine the normal distribution of the aggregated participant data. The correlation coefficients between the volumes of the ROI and the other proficiency scores were analyzed with Pearson's correlation coefficient for parametric data and Spearman's rank correlation coefficient for nonparametric data, respectively.

The volume of the ROI was compared between the two classes of board-certified and uncertified and between the three classes shown below. The participants were divided into three classes according to their ESS-OSATS score (the top 1/3, the middle 1/3, and the bottom 1/3 of ESS-OSATS score). The participants were also divided into three classes according to the number of experienced cases (the top 1/3, the middle 1/3, and the bottom 1/3 of the experienced cases). The thresholds were set so that the number of participants in each class was equal. The Kruskal-Wallis followed by the Wilcoxon rank-sum test were applied for comparison among the three groups. The Wilcoxon rank-sum test was also utilized for comparison of the volume of the ROI between board-certified and uncertified. The significance level was defined as a p-value of less than 0.05. All the analyses were performed using JMP 11 (SAS Institute Inc.). The 3D-CG models were created, and analyses performed, by individuals blinded to the surgical participants information.

RESULTS

Participant demographics

In the simulation surgeries, 46 cases were analysed, excluding one subject with a skull base injury. Table 1 shows a summary of participants' backgrounds. Among the 46 participants, 28 were board-certified while 18 were uncertified. The ESS-OSATS scores for board-certified participants were significantly higher than for uncertified (63.61±11.54 for board-certified participants and 43.50±11.31 for uncertified, $p<0.0001$). Table 2 shows the classification of the participants based on the ESS-OSATS scores. The number of previously performed surgical cases was 352.32±613.76 for board-certified and 10.17±15.09 for uncertified surgeons. Table 3 shows the results of dividing the participants into three classes based on the number of experienced cases.

Comparison of volume of ROI based on board certification

The volume of the ROI in postoperative models was 24.48±4.34 [cm^3] across all participants. One participant's model had to be excluded from this study due to a large skull base defect.

The ROI was significantly higher for board-certified participants (certified; 25.51±4.22 [cm^3] vs. uncertified; 22.87±4.14 [cm^3], $p=0.0307$) (Fig. 3).

Comparison with ESS-OSATS

A significant positive correlation was found between ESS-OSATS and the volume of the ROI ($r=0.7179$, $p<0.0001$) (Fig. 4. A). The volume of the ROI in the top 1/3 of ESS-OSATS score was significantly larger than those in the middle and bottom 1/3 (the top 1/3; 28.38±2.47 [cm^3], the middle 1/3; 23.78±3.28 [cm^3], and the bottom; 1/3 21.32±3.92 [cm^3]) (Fig. 4. B).

Comparison with the number of experienced cases

The volume of the ROI was analysed in association with experienced ESS-cases. Spearman's rank correlation coefficient revealed a significant positive correlation between the number of experienced cases and the volume of the ROI ($r=0.5123$, $p=0.0003$) (Fig. 4. C). The volume of the ROI in the top 1/3 of the number of experienced cases was significantly larger than those in the middle and bottom 1/3 (the top 1/3; 27.08±3.24 [cm^3], the middle 1/3; 23.60±4.44 [cm^3], and the bottom 1/3; 22.42±4.09 [cm^3]) (Fig. 4. D).

Comparison of progression with endoscopic evaluation

The completion of surgery within the allocated time was evaluated based on the 3D-CG of the ROI. Forty-one participants completed Step 2, 13 participants completed Step 5, and 5 participants completed Step 6. A representative example of 3D-CG is shown in Fig. 2. A representative case from the bottom 1/3 of ESS-OSATS score is shown in Fig. 2 (A, B, and C) and that from the top 1/3 is in Fig. 2 (D, E, and F). The endoscopic evaluation showed that 45 participants completed Step 2, 27 participants completed Step 4, 25 participants completed Step 5, and 12 participants completed Step 6. A comparison of the results of the 3D-CG assessment with those from visual assessment of the recorded endoscopic video are shown in Table 4. With the endoscopic evaluation as the standard, the accuracy of the 3D-CG judgement for presence of a surgical middle meatal antrostomy, sphenoidotomy, and frontal sinusotomy were 91.3%, 69.6%, and 84.8%, respectively. The sensitivity and specificity of middle meatal antrostomy were 91.1% and 100%, respectively. The sensitivity and specificity of sphenoidotomy were 48.0% and 95.2%, respectively. The sensitivity and specificity of frontal sinusotomy were 41.7% and 100%, respectively.

DISCUSSION

To our knowledge this is the first such study to examine the feasibility of surgical skill assessment using CT images of 3D sinus models after simulation surgeries of its kind in any surgical field, with all other previously published studies in other surgical disciplines (urology, cardiology, orthogeriatric, and so on) [10-12] using 3D analysis of CT scans for preoperative planning or surgical simulation rather than, for skills assessment.

The methods described above provide a tool for the assessment of surgeons training in ESS based on the change in total volume of the paranasal sinuses (quality) and their ability to progress through surgical steps in a given time period (efficiency). The methods also showed a high positive correlation to conventional assessment methods such as ESS-OSATS and the number of experienced cases. This positive correlation was found even when surgeons without any previous ESS experience were excluded in the analysis (data not shown).

Several methods have previously been described for assessing ESS proficiency, such as ESS-OSATS and the number of previous ESS cases. ESS-OSATS is a well-designed method but is labor-intensive, time-consuming and associated with subjectivity, as each recorded video is evaluated by assessors. Pleasingly despite its subjectivity high interrater validation has been documented [13]. Although one would expect a higher level of skills in more experienced surgeons who have performed more cases, this is not always the case and may not reflect actual proficiency. In the present study, we assessed the morphological change of the paranasal sinuses by analysing their CT images. In contrast to imaging human specimens, dozens of 3D model CTs can be imaged simultaneously. The image analysis can also be automated with a standard laptop due to the standardized paranasal sinus anatomy of the 3D printed models. These advantages not only remove the subjectivity of the assessment process but also are less laborious and time consuming in the assessment of ESS skills.

To the contrary, additional costs and resources are required when considering the implementation of the present methods in real-world situations. This is especially true when compared to ESS-OSATS, which can be done only with paper-printed checklists. However, besides the 3D models, the only ones used were commercially available laptop PC and clinical CTs, which most educational facilities have already equipped. Since the CT image processing is done using software available at no cost, no additional expenses are incurred. In terms of time efficiency, scoring the ESS-OSATS takes as long as the surgeries themselves (set to 45 minutes in this study), because the assessors are required to watch surgical videos all long. In contrast, our proposed method requires approximately one minute for 3D reconstruction from CT images and about 20 minutes for the construction of the ROI using the region growing method and its volume measurement. Therefore, the entire process can be completed in less than 30 minutes per case. Furthermore, unlike ESS-OSATS evaluations, our proposed method does not require specialized surgical expertise for scoring. Therefore, it has a significant advantage in user training, as it allows even non-specialists and trainees to perform objective assessments. Although ESS-OSATS, which can be adopted regardless of cost and resources, remains more practical, combining the two methodologies will contribute to a more comprehensive skill assessment.

To date there are only few studies using imaging to assess the completeness of surgery in patients with sinus disease. Several published studies have used the post-operative Lund Mackay score [14, 15], but this scoring system is more a reflection of disease extent than surgical completeness. To address this Okushi et al. proposed the residual ethmoid cell (REC) score to assess the completion rate of ethmoidectomy in postoperative CT images [16]. Although this is an excellent system, and does allow an indirect assessment of surgical proficiency, the extreme variability of sinus anatomy in humans, makes it difficult to make direct head to head comparisons between surgeons.

In this study, region growing method was applied. Region growing method is a popular method for image analysis in the field of information technology. However, if it was applied as it is for the paranasal sinuses, whose cells are all spatially continuous to the anterior nostrils due to natural drainage pathways, the ROI would always be all the sinuses regardless of pre- or post-surgeries and would not reflect the surgical proficiency. It is therefore necessary to introduce a threshold for the width of the corridor within the sinuses. The threshold of 4.00 mm was chosen because [9] reported that 3.95 mm is the minimum dimension to ensure penetration for maximum efficacy of topical sinus medications, however the threshold may not accurately reflect surgical completeness or clinical relevance. Therefore, in this study, various thresholds from 2.0 mm to 6.0 mm were also tested, resulting in similar results (see Supplementary figure 1 for results for thresholds of 3 mm, 4 mm, and 5 mm). As shown in Supplementary figure 1 (C), when the threshold is 5.0 mm, it is difficult to distinguish between the bottom 1/3 and middle 1/3, but the top 1/3 is clearly different from the bottom 2/3 and can be easily distinguished. When the threshold is 3.0 mm, as in the case of 4.0 mm, there are clear differences between the bottom 1/3, middle 1/3, and top 1/3 groups. Therefore, regardless of the threshold, it is possible to distinguish surgical skill based on ROI volume.

As shown in Table 4, the sensitivity of the 3D-CG-based Region of Interest (ROI) detection was lower for sphenoidotomy and frontal sinusotomy than middle meatus antrostomy. This discrepancy can be attributed to the different criteria for the achievement of a surgical step between the two assessment methods. In the video-based assessment, a surgical step was considered achieved if the ostium of sinuses was widened to any extent, regardless of the size of the opening. In contrast, in the 3D-CG-based ROI assessment, the step was judged as achieved only when the ostium widened enough for the sinus to continue to the anterior nostril with a width of more than 4.00 mm kept. That is, the criteria for the 3D-CG-based ROI assessment were stricter than the video-based assessment. As the video assessment was used as the gold standard in this study, this led to the ROI-assessment exhibiting low sensitivity and high specificity. This is especially true in cases of the sphenoid and frontal sinuses, which tend to have more narrow openings than the maxillary sinus.

This study has several limitations. Although the 4 mm threshold for an adequately opened sinus ostium was set with goal of producing a sinus cavity amenable to high volume nasal irrigation, the result did not guarantee whether the water actually washed out the segmented space when nasal rinsing. Secondly, the assessment of the presence of complications such as orbital breach, skull base injuries, catastrophic bleeding, and nasal septal perforation were not included in this current study, but would be necessary in any complete assessment of surgical proficiency. As the model is designed to be inserted into and detached from the face-basement every training, the medial orbital wall, internal carotid arteries, and the skull base of the model is exposed and can be easily investigated from outside for complications [17]. Indeed, five complications were found among the 47 surgeries, including injuries to the nasolacrimal duct (n=3), lamia papyracea (n=1), and the skull base (n=1) [6]. The model with the skull base injury was excluded from this study as the defect was over 4 mm and the ROI could not be measured, while the others were included as the defects were less than 4 mm. This suggests that other evaluations, such as postoperative reviewing of 3D models from outside, are necessary to assess safety. Also, the proposed method could not evaluate bleeding management as current 3D models cannot replicate bleeding. The methodology of this study was also unable to assess for preservation of the middle and superior turbinates, two key landmarks in sinus surgery. In the assessment, it could be highly evaluated in cases where the turbinates are resected, as the ROI would be enlarged; however, the unnecessary resection of the turbinate carries the risk of empty nose syndrome. In the future, it would be beneficial to establish standardized assessment methods for the proper preservation of anatomical structures, such as automatic image analysis, to compare the shape and position of turbinates before and after simulation surgeries. With the advantage of 3D-printed models replicating the turbinates at the same position, shape, and size, automatic image analysis could be easily achieved. Further studies will be necessary to establish comprehensive assessment frameworks. Third, only one form of 3D printed models was used in this study. Further study is necessary to examine if the postsurgical assessment of CT scans described in this study can be generalized to other forms of 3D printed models. As some participants also performed simulation surgeries for the left (contralateral) side of the model, we attempted to create the CG images of the ROI with the same method, finding similar results. (data not shown). This implies that the method could apply to other models with different anatomies, although further validation is necessary. In addition, even if evaluations can be established, future real-world studies are needed to determine whether the evaluation methods contribute to safety and outcomes in clinical cases. Lastly, skill sets for the region growing method in image analysis are required for assessors when considering the implementation for clinical and educational situations. Despite these limitations, this pilot study demonstrates the potential of combining the 3D printed models with CT image analysis to assess surgical skill, to provide a simple and objective measure of post-operative surgical outcomes under standardized conditions.

CONCLUSION

The use of 3D printed sinus models with standardized anatomy and CT image analysis provides a simple and objective tool for assessment of skill in ESS.

AUTHOR CONTRIBUTIONS

KY, MS, AJP, PJW, and AK designed the project. MS, KMi, AN, RW, SKi, TSu and AH organized the simulation training and collected data. MS and YN analyzed OSATS score. KY, KS, KE, KMa and AK measured the volume. KY, TT, XC, SKo and Tse analyzed the volume data. KY, MS, DH, AZ, AJP, and PJW wrote the draft. All authors provided feedback on the manuscript and gave final approval to the submitted paper.

ACKNOWLEDGEMENTS

We would like to thank KARL STORZ, Medtronic, and Stryker for providing the endoscopes, surgical equipment, and instruments.

DISCLOSURE STATEMENT

This work was partially supported by JSPS Grant-in-Aid for Scientific Research JP18H04102, 22 K16923, 22 K10599, and 25KJ0462. As conflicts of interests, MS: speaker’s bureau for Stryker. AJP: consultant for Fusetec, Medtronic, ENT technologies, Tissium, and Aerin Medical, shareholder of Chitogel, and speaker’s bureau for Sequiris. PJW: consultant for Fusetec and receiving royalties from Fusetec. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TABLE

Table 1. Characteristics of Participants

Characteristics		Certified	Uncertified
Years of Otolaryngologist			
	0-10	5 (10.9%)	18 (39.1%)
	11-20	15 (32.6%)	0 (0%)
	21-	8 (17.4%)	0 (0%)
Previous experience with ESS cases			
	0	0 (0%)	5 (10.9%)
	1-10	1 (2.2%)	8 (17.4%)
	11-50	9 (19.6%)	5 (10.9%)
	51-200	9 (19.6%)	0 (0%)
	201-	9 (19.6%)	0 (0%)
Sex			
	Male	24 (52.2%)	16 (34.8%)
	Female	4 (8.7%)	2 (4.3%)
Dominant hand			
	Right	26 (52.2%)	17 (37.0%)
	Left	2 (8.7%)	1 (4.3%)

Table 2. Categorization of participants based on ESS-OSATS score.

	Range of ESS-OSATS	Number of participants
The top 1/3	65-90	15 (32.6%)
The middle 1/3	49-64	16 (34.8%)
The bottom 1/3	18-48	15 (32.6%)

Table 3. Categorization of participants based on number of experienced cases

	Number of experienced cases	Number of participants
The top 1/3	100-3000	17 (37.0%)
The middle 1/3	21-99	13 (28.3%)
The bottom 1/3	0-20	16 (34.8%)

Table 4. Comparison of the difference between the endoscopic findings and the 3D-CG findings of ROI

Middle meatal antrostomy (Step 2)		Assessment with 3D-CG	
		Completed	Uncompleted
Assessment with recorded Endoscopic video	Completed	41	4
	Uncompleted	0	1

Sphenoidotomy (Step 5)		Assessment with 3D-CG	
		Completed	Uncompleted
Assessment with recorded Endoscopic video	Completed	12	13
	Uncompleted	1	20

Frontal sinusotomy (Step 6)		Assessment with 3D-CG	
		Completed	Uncompleted
Assessment with recorded Endoscopic video	Completed	5	7
	Uncompleted	0	34

FIGURES LEGENDS

Figure 1. The CT image of the sagittal plane shows the volumetric measurement flow.

The actual measurement was performed in three dimensions, although this figure shows only the sagittal plane as an example. The yellow part is the bony wall of nasal cavity and paranasal sinuses after the surgery. The brown part is the expansion area. The green part is the result of region growing. The light blue part is the region of interest (ROI). The red point is the seed point. (A) The CG model was constructed from CT images (yellow). (B) The anterior nostril, frontal sinus, and maxillary sinus were blocked to prevent the region growing method from spreading outside. (C) The walls of the paranasal sinus were inflated to virtually block the pathways of 4 mm or less. (D) Using the anterior nostril as the seed point (Red), the region growing method was performed (Green). (E) The walls of the nasal cavity that had been inflated were returned. (F and G) The ROI was obtained by inflating the segmented area. (H) The volume of the ROI was measured. Note that in this representative case, the participant completed the maxillary and ethmoid sinuses but was unable to create a pathway of 4.00 mm or more to the sphenoid and frontal sinuses. Therefore, the ROI contains the maxillary and ethmoid sinuses but not the sphenoid and frontal sinuses.

Figure 2. The CG models constructed from CT images of postoperative 3D sinus models.

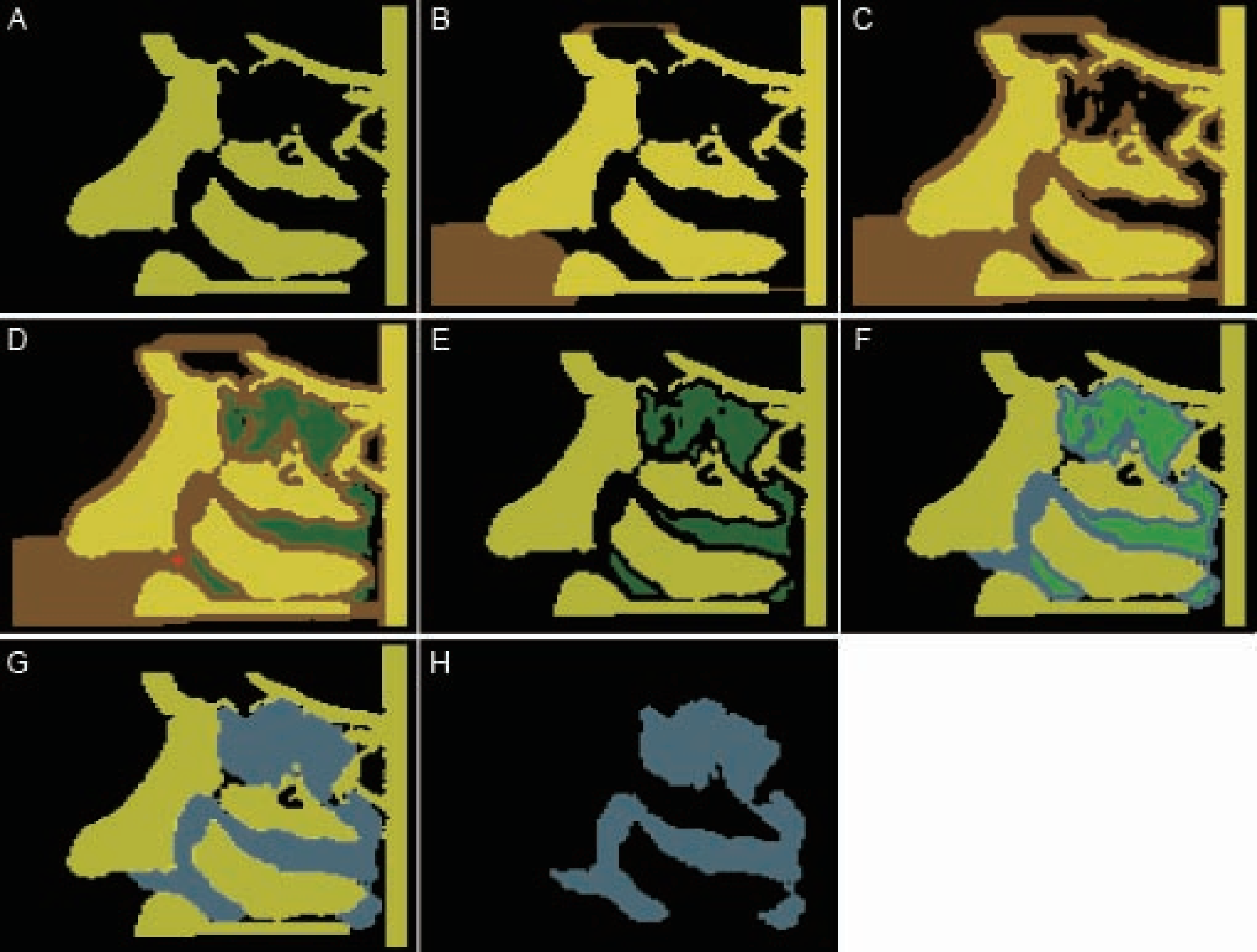
Representative CG models of uncertified and board-certified surgeons were compared. View of sinus (yellow) and the region of interest (ROI) (light blue) from the sagittal (A, D), coronal (B, E), and axial (C, F) planes. The ROI is shown for an uncertified surgeon in A, B and C, and ROI for a board-certified surgeon in D, E and F.

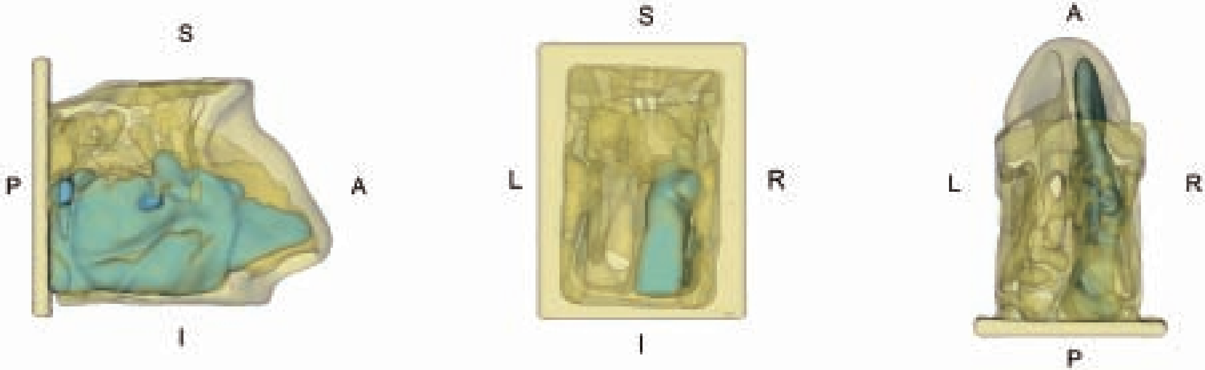
Figure 3. The volume of the region of interest (ROI) for board-certified and uncertified.

Figure 4. Comparison results of other ESS proficiency indices and the volume of the region of interest (ROI).

(A) Correlation between the volume of the ROI and the Objective Structured Assessment of Technical Skills score of the ESS. (B) Box plot of volume of the ROI in three classes by the Objective Structured Assessment of Technical Skills score of the ESS. (C) Correlation between the volume of the ROI and the number of experienced cases. (D) Box plot of volume of the ROI in three classes by the number of experienced cases.

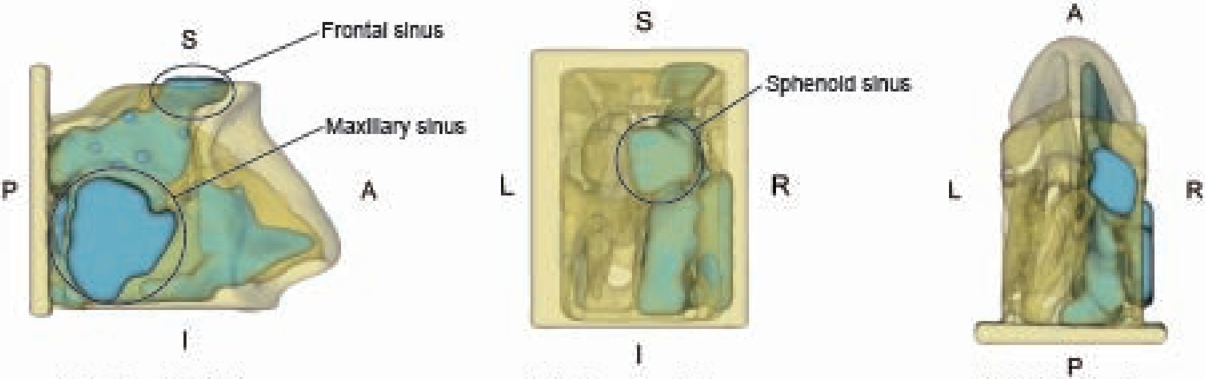
Supplementary figure 1. Box plots of volume of the ROI in three classes by the Objective Structured Assessment of Technical Skills score of the ESS for various thresholds.


A
B
C
D
E
F
G
H



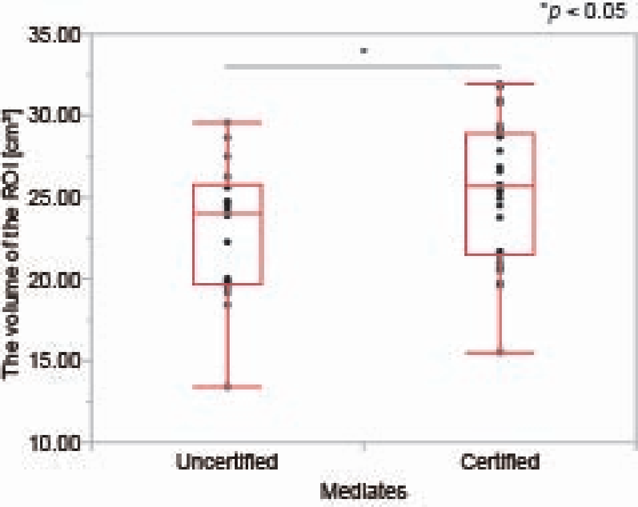
(A) Sagittal view (B) Coronal view (C) Axial view

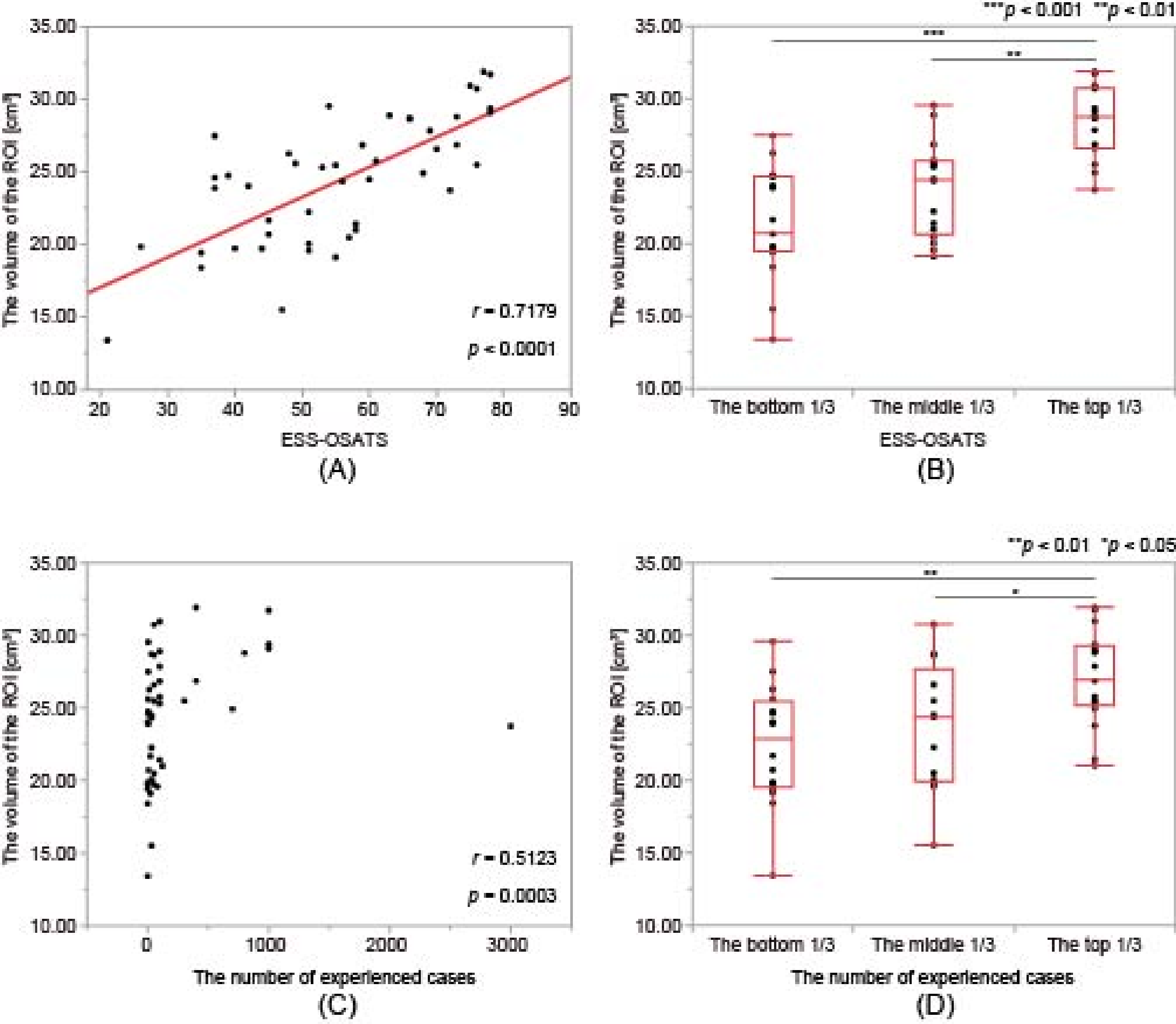
Representative case of uncertified



(D) Sagittal view (E) Coronal view (F) Axial view

Representative case of board-certified


*p < 0.05
35.00
30.00
25.00
20.00
15.00
10.00
The volume of the ROI [cm³]
*
Uncertified
Certified
Mediates



The volume of the ROI [cm³]
ESS-OSATS
r = 0.7179
p < 0.0001
(A)
***p < 0.001 **p < 0.01
The bottom 1/3
The middle 1/3
The top 1/3
(B)
The number of experienced cases
r = 0.5123
p = 0.0003
(C)
**p < 0.01 *p < 0.05
(D)