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RESEARCH

Marker-free registration for the accurate integration of CT images and the subject's anatomy during navigation surgery of the maxillary sinus

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Objective: This study compared three marker-free registration methods that are applicable to a navigation system that can be used for maxillary sinus surgery, and evaluated the associated errors, with the aim of determining which registration method is the most applicable for operations that require accurate navigation.
Methods: The CT digital imaging and communications in medicine (DICOM) data of ten maxillary models in DICOM files were converted into stereolithography file format. All of the ten maxillofacial models were scanned three dimensionally using a light-based three-dimensional scanner. The methods applied for registration of the maxillofacial models utilized the tooth cusp, bony landmarks and maxillary sinus anterior wall area. The errors during registration were compared between the groups.
Results: There were differences between the three registration methods in the zygoma, sinus posterior wall, molar alveolar, premolar alveolar, lateral nasal aperture and the infraorbital areas. The error was smallest using the overlay method for the anterior wall of the maxillary sinus, and the difference was statistically significant.
Conclusion: The navigation error can be minimized by conducting registration using the anterior wall of the maxillary sinus during image-guided surgery of the maxillary sinus.
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Keywords: registration; image-guided surgery; navigation; maxillary sinus

Introduction

It is well known that the posterior maxilla is the most compromising site for dental implant placement owing to poor bone quality and limited bone quantity. The limited bone volume for dental implant placement arises from destruction of the alveolar ridge and pneumatization of the maxillary sinus. Several surgical techniques have recently been developed to enhance the success rate of dental implants on the posterior maxilla;[1] the sinus grafting procedure is one of the main techniques used to overcome this vertical deficiency.[1–3]

Maxillary sinus bone grafting can be achieved via a lateral or a crestal approach. The crestal approach is recommended when the remaining bone height is 7–8 mm, because it is less invasive than the lateral approach. If the remaining alveolar bone height is less than 5 mm, the lateral approach is recommended for a maxillary sinus graft for either delayed or simultaneous placement of the dental implant.[3–6]

The successful completion of a maxillary sinus bone graft via the lateral approach is difficult for inexperienced operators. The biggest problem is that excessive intraoperative haemorrhage may occur if the posterior superior alveolar artery is damaged.[4,6,7] Moreover, if the bony opening is incorrectly located, it may be difficult to visualize and access the surgical site with surgical instruments, so that the sinus membrane is easily torn. In addition, the presence of a septum—which is an

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anatomical variation that is frequently observed in the maxillary sinus—makes it more difficult to detach the mucoperiosteum in the area, and bone grafting may not be successful when the maxillary sinus membrane is perforated.[4,6,7]

Recent developments in computer technology have increased the popularity of pre-operative surgical simulation and intraoperative navigation surgery based on three-dimensional (3D) images.[8,9] A "navigation operation" refers to the surgical method in which the image data, patient and operative tools are interconnected during the registration process in the operating room, based on the operative image data, and the real-time locations of the moving operative tools are visualized in the images.[10] The advantages of navigation operations are that major anatomical structures that are not easily seen by the naked eye can be visualized in real time, and the operation can be performed with minimal invasiveness and implemented according to the pre-operative treatment plan. In the fields of oral and maxillofacial surgery, the application of navigation operations is increasing for trauma, malignant cancer, maxillofacial deformities, and especially in implant procedures and bone grafting.[11–13]

The quality of the computer-assisted navigation operation is closely related to the level of accuracy, which itself is affected by technological, image, registration, application, human or other errors.[14–16] The most important of these is the registration error that is generated when aligning the imaged data of the patient with their actual anatomical body parts.[15,16] Since the registration accuracy has a direct effect on the accuracy of the navigation surgery, several methods have been developed to reduce that error.[17–19] The conventional 3D registration method is based on 3D coordinates with more than three points; registration methods with multiple markers have been used frequently because the error is larger when fewer points are used.[19,20] Marker-based registration has been widely used, with efforts being made to reduce any errors by increasing the number of markers or expanding the 3D region. However, registering 3D structures with only a few points has limitations, and distinctive markers need to be installed for the imaging before the procedure begins.[18,19] Thus, marker-free registration, which refers to registration methods that use anatomical landmarks or surface scanning based on the patient's actual anatomical structures,[17–19] has recently become the focus of interest.[17]

In the present study, we compared three marker-free registration methods that are applicable to a navigation system that can be used for maxillary sinus surgery. We evaluated the errors involved and established which registration method is the most applicable for accurate navigation operations.

Materials and methods

Digital modelling

The subjects of this study were ten craniomaxillary models (Model A20; 3B Scientific, Hamburg, Germany). CT images of the individual maxillofacial models were obtained with a SOMATOM® Sensation 64 system (Siemens Medical Solutions, Malvern, PA) under the following conditions: pixel size, 0.4375 mm; resolution, 512×512 pixels; field of view, 22.40 cm; H60f algorithm; and 0.4 mm slice thickness. The digital imaging and communications in medicine (DICOM) files were extracted from the CT data of the maxillofacial images.

The individual DICOM files were opened in Mimics v. 14.0 (Materialise, Leuven, Belgium), and the CT data were reconstructed in three dimensions and converted into the stereolithography (STL) file format using the STL conversion function in Mimics. The greyscale threshold for the 3D reconstruction of the CT data was set between 226 and 3071, which were the designated values for the parameters of the Mimics software for the bones in the CT images. The same threshold was applied to all ten models. The quality of the 3D reconstruction was set up as the optimal 3D calculation in the Mimics software: a triangle reduction of 3, an interaction edge angle of 10° and a tolerance of 0.0547 mm.

All ten of the maxillofacial models were scanned in three dimensions with an optical, non-contact, 3D scanner (smartSCAN^{3D} Duo; Breuckmann, Meersburg, Germany). The camera resolution was 1.3 megapixels, and the accuracy was within ±15 µm. The individual files were saved in STL format.

The 3D-scanned, STL-formatted files and the STL files generated by the conversion of the CT DICOM files were imported into software that could accept STL data to produce a maxillofacial digital imaging model for verification of the registration. Using Rapidform XOV2 software (INUS Technology, Seoul, Republic of Korea), the STL files of the three-dimensionally scanned maxillofacial models and the STL files generated by converting the CT DICOM files were overlaid using the software's registration function tools, as for the registration procedure during an actual operation. The computer hardware included an Intel® Core™ 2 Quad Processor Q9550 (2.83 GHz; Intel Corporation, Santa Clara, CA) and an NVIDIA® GeForce® GTS 250 graphics card (NVIDIA, Santa Clara, CA).

Registration methods

The applied methods for the registration of the maxillofacial models utilized the tooth cusp, bony landmarks and maxillary sinus anterior wall area as reference points (Figure 1). A four-point registration method was used for the tooth cusp tip (Cusp group): the mesiobuccal cusps of the first molars on both sides and the mesial point of the incisal edge of the upper incisor were used as the reference points, in addition to the canine cusp on the same side of the maxillary sinus area that was examined for registration. The three-point registration method used for bone structural landmarks (Bone group) employed the lateral nasal aperture, infraorbital foramen and inferior zygomati-

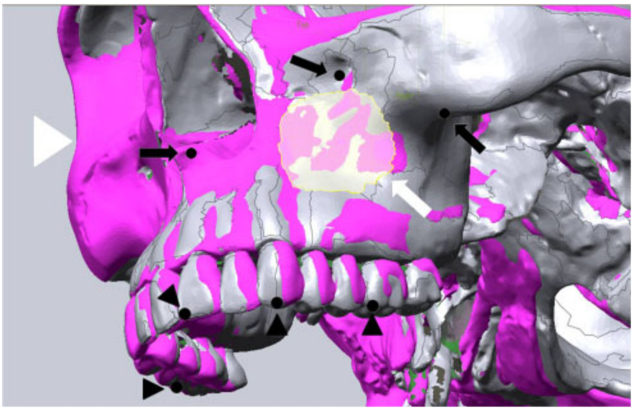

Figure 1 Stereolithography (STL) files of the three-dimensionally scanned maxillofacial models and the STL files generated by converting the CT data were overlaid using the three different registration methods in the software with maxillofacial digital model images. Black arrowheads: a four-point registration method was used for the tooth cusp: the first molar mesiobuccal cusp and the mesial point of the incisal edge of the upper incisor were used as the reference points, in addition to the canine cusps on the same side as the maxillary sinus registration. Black arrows: a three-point registration method was used for the bone structures: the lateral nasal aperture, infraorbital foramen and inferior zygomaticomaxillary suture on the same side as the maxillary sinus registration. White arrow: for the surface registration method, the anterior wall of the maxillary sinus was designated as the reference region on the software, and the defined surface was used for the registration. Light grey image: STL image generated by converting the CT data. Part of image indicated by white arrowhead: STL image of the three-dimensionally scanned maxillofacial model

comaxillary suture on the same side of the maxillary sinus. For the surface registration method (Surface group), the anterior wall of the maxillary sinus was designated as the reference region on the software, and the defined surface was used for the registration. When setting the reference points on the tooth cusps and the anatomical bone structures, the images were displayed three times larger than real size on the monitor screen.

Verification methods

In order to determine the error associated with the 3D reconstruction of the DICOM data from the CT images and the error from the conversion of the DICOM data into STL files, the 3D optical scanning data of one A20 model and the STL-converted files following CT imaging were registered over no particular region but over the entire craniomaxilla model with a minimum error range. The error in the entire model region was then measured with the mesh deviation function of the Rapidform software.

XOV2, which is a type of Rapidform software that has a specialized examination function, was used for comparing the STL files with the three aforementioned methods, which can be clinically applied to the registration. The error distance was measured automatically using the shortest error distance function of the software, and the absolute error values of the areas examined were recorded. The mean and standard deviation values were compared. Measurements were made on both the right and left sides for each of the ten models, four times on each side. Data were obtained from the 2 sides and the 10 models, giving a total of 80 error values for each area. The measured areas in which the error values were obtained were the zygoma, sinus posterior wall, molar alveolar, premolar alveolar, lateral nasal aperture and infraorbital areas. The statistical significance of any differences was tested by analysis of variance with SPSS® 14.0 software (SPSS, Chicago, IL).

Results

When the 3D optical scanning data of one A20 model and the STL-converted files following CT imaging were registered over no particular region, but over the entire craniomaxilla model with a minimum error range, the error was 0.070 ± 0.707 mm (mean $\pm$ standard deviation). There were differences between the registration methods in all of the measured areas (Table 1). The error was significantly smallest with the overlay method using the anterior wall of the maxillary sinus (Surface group) (Table 2). In the alveolar region of the molar and premolar areas, the error appeared to be smaller for the registration method using tooth cusps (Cusp group) than for the method using the bony landmarks (Bone group). With the tooth registration method (Cusp group), large errors were found in the zygoma and infraorbital areas.

For the side opposite to the registration area, the error for the bone registration method (Bone group) was large in the zygoma, the lateral nasal aperture and the infraorbital areas. For the side opposite to the registration area, the error for the surface registration method using the anterior wall of the maxillary sinus (Surface group) was large in the zygoma (Table 3).

Discussion

This study compared three image registration methods for maxillary sinus navigation operations using dental structures, anatomical bone structures and the surface of the anterior wall of the maxillary sinus as possible reference. The results show that the registration method based on the surface data of the anterior wall of the maxillary sinus produced excellent results overall.

Various errors can occur when performing image-assisted operations using a computer, including technological, image, registration, application and human errors.[14–16] Technological errors refer to measurement errors in the location of the navigation system based on optical triangulation, and they are generated by the original hardware and software. Image errors include those in the 3D reconstruction of CT images.

Technological errors should be taken into consideration when using navigational instruments such as the

Table 1 Registration errors according to registration methods for the maxillary sinus in image-guided surgery

	Registration method			
	Bone mark (n = *80*)	*Sinus surface* (n = *80*)	*Tooth cusp* (n = *80*)	
Location	*Mean* ± *SD (mm)*	*Mean* ± *SD (mm)*	*Mean* ± *SD (mm)*	p-*value*
Zygoma area	0.294 ± 0.284	0.105 ± 0.133	0.497 ± 0.472	<0.001[a]
Sinus posterior wall area	0.468 ± 0.335	0.179 ± 0.200	0.343 ± 0.464	<0.001[a]
Molar alveolar area	0.589 ± 0.422	0.195 ± 0.211	0.285 ± 0.372	<0.001[a]
Premolar alveolar area	0.509 ± 0.430	0.177 ± 0.223	0.291 ± 0.297	<0.001[a]
Lateral nasal aperture area	0.287 ± 0.205	0.137 ± 0.199	0.346 ± 0.335	<0.001[a]
Infraorbital area	0.301 ± 0.240	0.138 ± 0.187	0.421 ± 0.304	<0.001[a]

[a]Indicates statistical significance (limit set at $p < 0.05$).

tracking camera and the dynamic reference frame (DRF; attached to the patient or operative instruments). The optical navigation system can provide an accuracy of 0.1–0.4 mm in positioning, and the trackable region is generally about 100 × 100 × 100 cm.[21] A significant error can be generated if the vector angle between the optical camera, probe and operative instruments is larger than 60°; the vector angle should be smaller than 50° to reduce the error.[22] The electromagnetic navigation system has a narrower measurement region, and errors can be generated by metal instruments such as stainless steel surgical instruments.[23]

Image errors are dependent upon the image modes and are related to the sensor matrix size, slice thickness, voxel size, volume acquisition, signal-to-noise ratio, contrast, background structures, image distortion and software errors.[24] MRI has problems of motion artefacts and geometric inaccuracy because it has a longer scanning time, lower resolution and contrast, and limited visibility to bone tissue than CT. Cone beam CT has a smaller scan field (only 15–20cm) than multislice CT (MSCT), and is more accurate in the central region of the image.[25]

In this study, CT images were obtained with MSCT. The material used for the study was a manufactured craniofacial model, rather than fresh cadavers or dry skulls. The credibility of the results would have been higher if actual human bodies had been used. In a study using human bodies, cadavers should be used in the actual object measurement with CT or 3D optical scanning for the error test. However, when using cadavers there may be issues with tooth and bone defects, image artefacts from prosthodontics and soft-tissue preservation problems.

Even if a craniomaxillary model in which the soft tissue was recognized had been used, a model that allows for a clear distinction between soft tissues and bones is required if 3D optical scanning is to be conducted for error testing in the bone areas. A research model that reflects the characteristics of the human body including the soft tissues while simultaneously allowing for easy error testing is required in the future, and developments of such models are ongoing. Hence, the respective feasibilities of studies using human bodies including cadavers, and the construction and study of an experimental model that recognizes soft tissue may be verified in the future.

When converting the CT image data into STL file format, the results differ according to the 3D reconstruction protocol and the conversion algorithm for each of the software programs. In this study, the 3D optical scanning data of one model and the converted STL data after CT imaging were registered to no particular region, but rather to the entire craniomaxilla model with a minimum error range, and the mean error was 0.070 mm. The STL values converted from the scanning data of the model and the CT images were compared, but they included various errors based on the different settings in the CT equipment, the conversion software and the registration software. Future studies should verify the error range of each software program and the optimal protocol with respect to the application methods when converting DICOM files from CT data into STL files.

Registration is the process by which the coordinates of the image data are matched with the coordinates of the anatomical structures of the patient by navigation, and is the largest contributor to errors in image-guided operations.[15,16] Registration errors include the fiducial localization error, which is generated when searching for the paired fiducial points that are considered to be the same region in the image data and the patient's

Table 2 Registration error comparison and recommended registration method for the maxillary sinus in image-guided surgery

		p-*value (Tukey HSD between methods)*			
Location	*Error size order*	*Bone/surface*	*Surface/tooth*	*Bone/tooth*	*Recommended method*
Zygoma area	Tooth>bone>surface	0.001[a]	<0.001[a]	<0.001[a]	Sinus surface
Sinus posterior wall area	Bone>tooth>surface	<0.001[a]	0.010[a]	0.063	Sinus surface
Molar alveolar area	Bone>tooth>surface	<0.001[a]	0.234	<0.001[a]	Sinus surface/tooth cusp
Premolar alveolar area	Bone>tooth>surface	<0.001[a]	0.077	<0.001[a]	Sinus surface/tooth cusp
Lateral nasal aperture area	Tooth>bone>surface	0.001[a]	<0.000[a]	0.316	Sinus surface
Infraorbital area	Tooth>bone>surface	<0.001[a]	<0.001[a]	0.007[a]	Sinus surface

HSD, honestly significant difference.
[a]Indicates statistical significance (limit set at $p < 0.05$).

body; the fiducial registration error (FRE), which is generated in between the fiducial points of the image and the patient after the registration procedure; and the target registration error (TRE), which indicates an error between the image and the targeted body points after the registration procedure.[26] This study was conducted using the zygoma, sinus posterior wall, molar alveolar, premolar alveolar, lateral nasal aperture and infraorbital areas as the TRE anatomy areas.

In general, there are two methods of registration: marker-based and marker-free registration. Marker-based registration uses distinctive reference markers in the pre-operative image that are easily identified intraoperatively, such as bone-implanted screws, a dental splint aligned with the maxilla teeth and skin-applied reference markers. Marker-free registration employs the patient's own anatomical structures by means of anatomical landmarks or surface scanning. It has yet to be established unequivocally which is the more accurate method.[17–19] To register the same positions in the image and in the patient's body, the patient has to be firmly fixed on the operating table, or else a stereo camera that continually tracks the patient's motions or an electromagnetic position sensor DRF must be used.[15,27] Fiducial points such as anatomical markers or skin-applied markers or markers implanted in bones are used as corresponding points that match the image to the actual patient's body.[28,29] Markers that are manually or automatically defined in the computer should be larger than the image voxels and should be able to reproducibly, regularly and accurately set the position.[30] The FRE is calculated as the root mean square of the distance between the markers after the registration.[29,31] At least three non-planar markers that are located in different planes are usually required to avoid registration errors.[29] The present study designated three reference points on bone structures and four reference points on tooth cusps.

Errors generated by shifts in the skin or other factors in cases of the registration using skin-applied fiducial points,[32,33] can be avoided by using fiducial points on bones.[29,33] In the present study, reference points were designated on hard tissues such as teeth and bone structures (bony anatomical points and the bony surface). This also avoided the problem of facial soft tissues appearing different on pre-operative CT images due to the retraction of soft tissues at the surgical site during maxillary sinus surgery.

In this study, we investigated the feasibility of using bone surface data for image registration when the anterior wall of the maxillary sinus was exposed during navigation surgery of the maxillary sinus. The results showed that the surface scan data-based registration method could indeed be applied to the navigation operation of the maxillary sinus. Exposure of the bone surface is limited to cases where the periosteum is elevated. This method could have some limitations: (1) there could be a defect in the scanned image of the bone surface due to bleeding, (2) the area of the anterior wall

Table 3 Registration errors according to registration location for the maxillary sinus in image-guided surgery

	Method								
	Bone mark (n = *160*)			*Sinus surface* (n = *160*)			*Tooth cusp* (n = *160*)		
	Ipsilateral area (n = *80*)	*Contralateral area* (n = *80*)		*Ipsilateral area* (n = *80*)	*Contralateral area* (n = *80*)		*Ipsilateral area* (n = *80*)	*Contralateral area* (n = *80*)	
Location	*Mean* ± *SD* (*mm*)	*Mean* ± *SD* (*mm*)	p-*value*	*Mean* ± *SD* (*mm*)	*Mean* ± *SD* (*mm*)	p-*value*	*Mean* ± *SD* (*mm*)	*Mean* ± *SD* (*mm*)	p-*value*
Zygoma area	0.294 ± 0.284	0.733 ± 0.570	<0.001[a]	0.105 ± 0.133	0.227 ± 0.208	<0.001[a]	0.493 ± 0.471	0.578 ± 0.690	0.364
Sinus posterior wall area	0.468 ± 0.335	0.452 ± 0.450	0.796	0.179 ± 0.200	0.199 ± 0.150	0.470	0.342 ± 0.461	0.318 ± 0.432	0.737
Molar alveolar area	0.589 ± 0.422	0.578 ± 0.459	0.874	0.195 ± 0.211	0.184 ± 0.134	0.697	0.285 ± 0.372	0.313 ± 0.424	0.660
Premolar alveolar area	0.509 ± 0.430	0.621 ± 0.488	0.126	0.177 ± 0.223	0.212 ± 0.171	0.273	0.289 ± 0.296	0.320 ± 0.347	0.541
Lateral nasal aperture area	0.287 ± 0.205	0.443 ± 0.392	0.002[a]	0.137 ± 0.199	0.182 ± 0.200	0.156	0.346 ± 0.333	0.390 ± 0.430	0.474
Infraorbital area	0.301 ± 0.240	0.604 ± 0.468	<0.001[a]	0.138 ± 0.187	0.142 ± 0.158	0.885	0.420 ± 0.303	0.522 ± 0.595	0.174

[a]Indicates statistical significance (limit set at $p < 0.05$).

of the maxillary sinus exposed during the operation may not be sufficiently large and (3) access to the anterior wall of the maxillary sinus for scanning could be limited during the operation. Furthermore, a localization error could be generated during the procedure when setting the anterior wall region of the maxillary sinus scanned in an actual patient to the CT images. The protocol for image registration needs to be verified in the future.

Registration references should be widely located around the operation target, but the accuracy is higher when they are located near to the operated area.[20,34,35] In our study, the error was large in the alveolar bone area when bone structures were used. When the registration was performed using tooth cusps, the error was large in the infraorbital and zygoma areas. This confirms that it is better to perform registration near the operated area. Hence, intraoperative registration errors can be reduced by designating reference points at the maxilla for maxillary sinus surgery.

The error in the zygoma, premolar alveolar, lateral nasal aperture and infraorbital areas was larger on the side opposite to the registration area. Thus, the use of different registration methods in different maxillary sinus areas should be considered, rather than automatically performing maxillary sinus surgery on both sides based on the registration data from one side.

The present study employed image-overlaying software and an experimental model that excludes the error from the navigational equipment devices, so that even though there was an error, it was small because the error associated with the navigation equipment is likely to be greater than the registration error associated with the software. The registration error was smaller than that found in previous studies.[36–38] In a point-to-point navigation study using zygomatic screws as registration reference, Klug et al[36] found a mean error of 1.1–1.4 mm. In a TRE study using template-based registration, Eggers and Muhling[37] found mean errors of 1.57 mm in the anterior skull base and 3.31 mm in the lateral skull base. Finally, in a microscrew-based registration study using a cadaver skull, Zhang et al[38] found a mean error value of 0.93–3.19 mm.

Digital modelling and registration of the images were performed to exclude navigation equipment error in the present study. Every navigation system has its own innate and individual technological errors. The digital modelling-based registration method may be the best research method for establishing the most appropriate registration method for specific surgical anatomical structures.

The findings of this study led us to propose a registration method that can be applied clinically to an operation wherein the anterior wall region of the maxillary sinus is exposed. This method may reduce the risk of injuring the blood vessels—especially the posterior superior alveolar artery—during sinus floor elevation and bone grafting. It is assumed to be applicable to the operation over the regions of the infraorbital area, nasal cavity, the posterior area of the maxillary sinus and the zygoma area. The use of the anterior wall region of the maxillary sinus as a reference area may be appropriate in implantation surgery wherein sinus floor elevation and bone grafting via a lateral approach are conducted simultaneously. Conversely, in the case of flapless implantation, the maxillary sinus anterior wall surface-based registration cannot be utilized since the anterior wall region of the maxillary sinus is not exposed. However, our results show that it is feasible to use tooth cusps as reference points in the registration, although it has a greater range of error than maxillary sinus anterior wall surface-based registration for premolar and molar alveolar bone. Thus, registration using the tooth cusp can be used for surgery in the alveolar bone region and for flapless implantation.

Conclusion

We found that in most cases the navigation error was smallest when surface registration was conducted using the anterior wall of the maxillary sinus as a reference region. The navigation error can be minimized by conducting registration using the anterior wall of the maxillary sinus during image-guided surgery of the maxillary sinus.

In the alveolar region of the molar and premolar areas, there was not a significant difference between the tooth cusp registration error (Cusp group) and the registration error using the anterior wall of the maxillary sinus (Surface group). Both of these registration methods may be used in image-guided navigation surgery for the maxillary alveolar region.

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