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Image-to-patient registration by natural anatomical surfaces of the head

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Abstract: The use of registration markers in computer-assisted surgery is combined with high logistic costs and efforts.
During the preparation of image guided surgery, automated markerless patient-to-image registration based on anatomical surfaces allows a significant reduction of preoperative effort and of the radiation dose the patient is exposed to. Placement and measurement of radio-opaque fiducial markers becomes unnecessary. The usability of face, auricle, maxilla and mandible for surface-based registration to CT image data was investigated. The present study was performed to evaluate the clinical accuracy in finding defined target points within the surgical site after markerless patient registration in image-guided oral and maxillofacial surgery.
Preoperatively, the spatial position of 20 patients was registered to CT image data using a 3D laser surface scanner. Indications for surgery were tumours, foreign bodies and skeletal malformations. The accuracy of this surface-based registration was verified using additionally placed fiducial markers.
The study showed, that markerless surface-based registration was sufficiently accurate for clinical use when the surface used for matching was the upper jaw, the face, or - with reservations - the auricle. Surface-based registration using the mandible did not yield satisfying results. To conclude, image-to-patient registration based on laser surface scanning is a valuable method for surgery of the head. Multiple sites of the head were identified as appropriate for the method. Hence, dependent on the individual case and the intended surgery, the registration area can be selected with the necessary flexibility.

Keywords: Computer aided surgery, navigation, patient-to-image registration, calibration, laser

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1 Introduction

Computer aided surgery using frameless stereotaxy systems allows the intraoperative use of image data, e.g. Computer Tomography (CT) or Magnetic Resonance Imaging (MRI) to navigate instruments or tissue segments. Studies on the high level of accuracy and safety using these methods have been published. [1–4] However, several additional steps have to be performed by the patient and the physician before this technique can be applied:

The intraoperative situs has to be correlated to the preoperatively obtained image data. Generally fiducial markers are used, placed in or on the patient's body prior to imaging. They have to remain unchanged until surgery, or their reattachment at the identical position must be possible. [5–11]

In most cases diagnostic CT-imaging has already been performed without fiducial markers. In these cases an additional CT with fiducial markers has to be performed solely for the navigation purposes. This means additional costs, effort, and irradiation to the patient. Intraoperative registration of the fiducial markers is performed by the surgeon using an infrared tracked pointer [12–22] and is a major source of error [5, 9].

Hence, the purpose is to abandon marker-based registration. Markerless registration based on anatomical landmarks - e.g. tip of the nose, tragus - is not a satisfactory alternative: the accurate assignment of such landmarks in image data and intraoperative situs is difficult and yields a low registration accuracy [9]. However, registration using surfaces instead of distinct points can improve registration accuracy [9, 23–27].

Hence, registration using anatomical surfaces, is an alternative. Laser surface scanners allow accurate intraoperative analysis of anatomical surfaces [28]. The primary target for scanning would be the face [25]. However, in cases with facial swelling, trauma, or incomplete imaging of the soft tissues in the CT scan, the use of the auricle, the mandible or the maxilla was investigated as well.

The benchmark for the accuracy of surface-based registration was fiducial marker registration. Hence, 20 patients were also equipped with radio-opaque fiducial markers prior to CT imaging. After surface-based registration, a tracked infrared pointer was used to identify these fiducial markers. The aim of the study was to find out, how accurate patient registration can be performed using surface registration of different anatomical surfaces: the face, the auricle, the mandible, and the maxilla.

2 Statistical methods and Experimental Procedures

2.1 Patients

Before the beginning of the study, approval from the local ethics committee was obtained. The number of the approval of the local ethics committee was 096/2002.

After written, informed consent, twenty patients were enrolled, who suffered either from a tumour, a malformation of the skull or a foreign body (Table 1). Independent from the study, all patients had been scheduled for surgery using a navigation system.

Patient	Patient characteristics
1	tumour of the mouth floor
2	tumour of the pharynx
3	tumour of the mouth floor
4	tumour of the mouth floor
5	tumour of the upper jaw
6	foreign body retromaxillary
7	tumour of the mouth floor
8	tumour of the mouth floor
9	tumour of the upper jaw
10	tumour of the mouth floor
11	malformation of the skull (brachycephalus)
12	tumour of the mouth floor
13	tumour of the pharynx
14	tumour of the mouth floor
15	tumour of the mouth floor
16	tumour of the upper jaw
17	tumour of the mouth floor
18	tumour of the mouth floor
19	tumour of the pharynx
20	tumour of the mouth floor

Table 1 Detailed patient characteristics.

2.2 Experimental Procedures

The patient's position was measured using laser-scans of face (Fig. 2), auricle (Fig. 4), maxilla (Fig. 6) or mandible. Prior to imaging, conventional radio-opaque fiducial markers were attached to the patients via a dental template. The template was attached to the maxilla in cases of registration using the face, the auricle or the maxilla. In cases of surface registration using the mandible, the template was attached there as well. All patients had sufficient dentition to ensure a tight fit of the template. CT of the head was obtained with 2 mm axial slices (Volume Zoom, Siemens, Forchheim, Germany).

Laser-scan-based registraton was performed using the Surgical Segment Navigator (SSN++) navigation system that had been developed jointly with Carl Zeiss (Oberkochen, Germany). It has an integrated infrared tracking camera (Polaris, NDI, Waterloo, Canada) and is meanwhile equipped with a laser surface scanner [25, 29, 30].

CT image data was transferred to the SNN++ system for registration. Face and auricles could be segmented fully automatically. Mandible and maxilla were segmented semi-automatically. Pterygoid process and ramus ascendens, as well as dental metal artefacts were removed manually during segmentation.

Laser scan based registration was performed using a 3D-Scanner VI 900 (Minolta, Osaka, Japan). Strips of laser light (wave length: 690 nm) were projected onto the object and three dimensional coordinates were triangulated for every point on the surface. Within 2.3 seconds, 640 x 480 points were recorded. The geometric resolution of the scanner is, dependent on the distance of the object, up to 0.17 mm in the x-y plane and 0.047 mm in z-distance. The scanner was mounted on a stand above the operation field (Fig. 1).

Laser scans of auricle, maxilla and mandible were recorded using a lens with a focal length of 25 mm. Laser scans of the face were performed using a lens with a focal length of 14.5 mm. This was done in order to utilize the field of view optimally and to record as many surface points as possible.

Surface scan data was transferred to the SSN++ workstation via SCSI-line. There, matching with preoperative CT image data and registration were performed. After registration, the coordinates of all fiducial markers were displayed by the system. These coordinates were compared to the fiducial marker positions measured with an infrared tracked pointer. The euclidean distance d_{marker} between the fiducial marker position measured by the infrared tracked pointer, and the position calculated from the surface registration was assumed as the precision of registration.

2.3 Statistical analysis

Statistical analysis and comparison of two measures was performed in the test records of patients with and without auricle deformation during CT scanning using an unpaired two-sided t-test [31].

Where t is

$$|t| = \frac{|m_1 - m_2|}{\bar{s} - \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

with m_1 = mean deviation in test record 1 and n_1 = number of test records in test record 1 and

$$\bar{s} = \sqrt{\frac{(n_1 - 1) \cdot (s_1)^2 + (n_2 - 1) \cdot (s_2)^2}{n_1 + n_2 - 2}}$$

with s_1 = standard deviation of test record 1. m_2, n_2 and s_2 define the corresponding mean deviation, number of records and standard deviation in test record 2. The number of records was 15 in patients with auricle deformation and 9 in patients without auricle deformation.

The critical t is $t_1 \rightarrow \propto n_1 + n_2$. We took a = 5% and found within a table for the critical t for the t-test 2.07 for $n_1 + n_2 - 2 = 22$ [15]. A t-test delivering a result above the critical t indicated a different distribution of the test records with significance.

3 Results

Markerless registration using the surface of the face (Fig. 3) was achieved with an average accuracy of 1.1 mm ($\sigma \pm 0.30$ mm) with a range from 0.2 - 1.8 mm (Table 2). The 95% percentile was at 1.6 mm.

Patient	Marker 1	Marker 2	Marker 3	Laser points
1	1.3	1.4	0.8	132,076
2	1.0	0.9	1.2	141,822
3	0.8	1.4	1.1	148,540
4	1.3	0.9	1.3	156,210
5	1.2	0.2	0.5	139,836
6	1.4	1.2	1.1	145,364
7	1.3	1.4	1.3	150,428
8	0.6	1.2	1.4	144,838
9	1.0	1.6	1.3	130,960
10	1.6	1.2	1.3	141,198
11	0.8	0.6	1.2	149,062
12	1.0	1.4	1.3	152,524
13	1.8	1.2	0.6	146,376
14	1.2	1.2	1.3	138,680
15	0.9	1.1	1.4	140,795
16	1.3	0.9	1.3	148,650
17	1.0	1.1	0.9	151,892
18	0.8	1.4	1.5	142,008
19	0.8	1.1	1.4	147,256
20	1.5	1.3	0.8	150,862

Table 2 Accuracy of detection (in mm) of intraoral markers in regions 16, 11, and 26 after laser surface registration of the face.

Markerless registration using the surface of the maxilla (Fig. 5) was achieved with an average accuracy of 0.8 mm ($\sigma \pm 0.3$ mm) with a range from 0.2 - 1.5 mm (Table 3). The 95% percentile was at 1.2 mm. Hence, face and maxilla were reliable structures for intraoperative surface registration.

Both attempts of patient registration using the mandible failed. The highly mobile structures of tongue and floor of the mouth caused an incongruence of the surfaces of the mandible in CT and laser surface scan. Hence the SNN++ workstation could not correlate the surfaces.

Registration results using the auricle (Fig. 7) were widely scattered with an average accuracy of 2.9 mm ($\sigma \pm 1.4$ mm) with a range from 0.8 - 7.4 mm (Table 4). The 95% percentile was at 5.2 mm. Further analysis revealed that in five cases the auricles had temporarily been bent by the headrest during CT imaging (Table 4, cases #1, #3, #4, #7, #8), as seen in Fig. 8. These were the cases with high inaccuracies and an average

Patient	Marker 1	Marker 2	Marker 3	Laser points
1	0.5	0.9	1.2	63,268
2	0.8	1.0	1.5	56,930
3	1.1	0.8	0.2	61,442
4	0.9	0.5	0.6	64,570
5	1.2	1.0	1.0	58,056
6	0.8	0.4	1.0	50,805
7	0.5	1.0	0.8	68,244
8	1.2	1.1	0.8	56,256
9	0.3	1.2	0.9	62,020
10	0.8	0.6	0.8	57,988

Table 3 Accuracy of detection (in mm) of intraoral markers in regions 16, 11 and 26 after laser surface registration of the maxilla.

deviation of 3.4 mm ($\sigma \pm 1.4$ mm).

Patient	Marker 1	Marker 2	Marker 3	Laser points
#1*	3.0	2.4	4.3	45,802
#2	2.0	3.6	2.8	36,866
#3*	4.1	5.2	7.4	52,650
#4*	4.3	2.7	2.8	48,048
#5	1.2	0.8	1.1 53,932	
#6	1.9	2.5	1.4	46,474
#7*	2.6	3.1	3.5	50,360
#8*	2.4	2.1	1.6	51,682

* indicates auricle deformation in head support of the computer tomograph

Table 4 Accuracy of detection (in mm) of intraoral markers in regions 16, 11 and 26 after laser surface registration of the auricle.

The remaining cases where the auricles had not been in contact with the headrest during CT imaging showed a better average registration accuracy of 1.9 mm ($\sigma \pm 0.9$ mm). This difference was statistically significant:
m1 = mean deviation of accuracy in test records with auricle deformation, m1 = 3.4 mm.
n1 = number of test records with auricle deformation, n1 = 15.
s1 = standard deviation of accuracy in test records with auricle deformation, s1 = 1.4 mm.
m2 = mean deviation of accuracy in test records without auricle deformation, m2 = 1.9 mm.
n2 = number of test records without auricle deformation, n2 = 9.
s2 = standard deviation of accuracy in test records without auricle deformation, s2 = 0.9 mm.

The t-test delivered 2.86 which is above the critical t of 2.07; that means, the difference between the accuracy of test records with and without auricle deformation was statistically significant.

4 Discussion

For the further development of image guided oral and maxillofacial surgery new concepts are necessary that better adapt to the clinical and surgical workflow.

Image guided surgery not relying on special imaging with registration markers, but performed using any CT or MRI image data would represent a major progress. In this study, the fiducial markers mounted on dental splints were used for evaluation only and are not necessary for future surface scan-based registration.

An automated registration method that releases the surgeon from the task of manual correlation of patient and image data would represent a further progress. Advanced automated registration techniques that are not based on individual markers, but use surface-based methods, address these two issues.

Registration using the surface of the face proved to be accurate and reliable. However, in cases of trauma and/or swelling, the facial surface might change rapidly between CT imaging and registration. Hence, alternative regions were evaluated for their suitability for surface registration as well.

Registration based on the surface of the maxilla yielded excellent results, because the markers for the accuracy check on the dental splint were situated closely to the registration surface. However, it is to be expected that in regions more remote to the maxilla, like the orbit or the calvarium, registration accuracy will decrease. [25, 32] Here registration based on facial surfaces might be clinically more accurate. Furthermore, the need of preoperative manual processing of the image data to remove dental metal artefacts or the processus pterygoidei means additional effort for maxilla-based registration and takes about 10 to 15 minutes.

Registration based on the surface of the mandible proved to be clinically infeasible. In a single scan parts of the mandible were always covered. However, the use of a smaller scanning device that takes separate scans of the left and right mandible with the tongue moved to the opposite side, might be a solution to this problem. A system with a tracked handheld laser scanner, where the partial scans can be assembled, is currently under evaluation [33].

A reliable registration based on the surface of the auricle is possible if the design of the head rest and the position of the patient ensure that the auricle is not temporarily deformed during CT image data acquisition [34].

As a rule of thumb, the accuracy of registration of a target is better, the closer the target is to the area used for registration. [35] In our setup the accuracy measured for auricle-based surface registration was lower than for maxilla- or face-based registration. However, this might be related to the fact that the intraoral markers used for the accuracy check were particularly remote from the site of surface scanning.

However, dependent on the region of surgery the choice of auricle-based registration could be an advantage. If, e.g., surgery of the lateral skull base was planned, auricle-based registration might yield better accuracy than registration based on the now more remote surfaces of maxilla or face.

It is an inherent advantage of the concept of surface-based registration that the region optimal for the registration procedure is regularly imaged in diagnostic imaging as well, whereas in fiducial marker registration there is frequently the need to perform CT-Scanning of a more extended region. Furthermore, in cases where the image data of the optimal region for registration is clipped, alternative regions can be used for registration (e.g. the mandible, if the face is incomplete). [23, 25, 26]

Finally, an important point is the robustness of the concept. CT image data in this study had a slice thickness of 2 mm. This means considerably less radiation for the patient than in CT imaging with 1 mm slices frequently used for image guided surgery based on fiducial marker registration.

The SNN++ registration system differs from other concepts of surface-based registration. The z-touch system (BrainLab, Heimstetten, Germany) uses a laser pointer to record points reflected from the patient's surface with the same infrared camera used for tracking in the navigation-system (VectorVision, Brainlab, Heimstetten, Germany). The theoretical advantage of this approach is that the surface scan data is recorded in the same coordinate system as the later performed navigation. The SNN++ system has to calculate one additional transformation to match the coordinate system of the laser scanner and the that of the infrared camera. However, reports in literature showed a considerably less accurate registration with the z-touch system than was achieved in our study [36]. On the one hand this is explained the lower number of recorded points (z-touch: hundreds of points, SNN++ approx. 50,000 points for auricle and maxilla, approx. 140,000 points for the face, Tables 1-3) [37], on the other hand by the fact, that the spatial accuracy of infrared cameras generally used by navigation systems, (e.g. the Polaris) is lower (about 0.3 mm [38]) than the accuracy of the laser surface scanner used in this study. Furthermore, the laser spot is distorted if it is not projected orthogonally onto a flat area of the skin. Hence the calculated coordinates of the centre of the spot might lie above or below the patients surface. This might add to this systems inaccuracy.

In conclusion, our results show that the use of markerless surface-based registration methods using the surfaces of face, maxilla or auricle can reduce effort and cost of image-guided interventions in maxillofacial surgery, ENT surgery and neurosurgery. The accuracy is in the same order of magnitude as that of conventional marker based methods.

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Fig. 1 Laser surface scanner mounted on an adjustable stand.

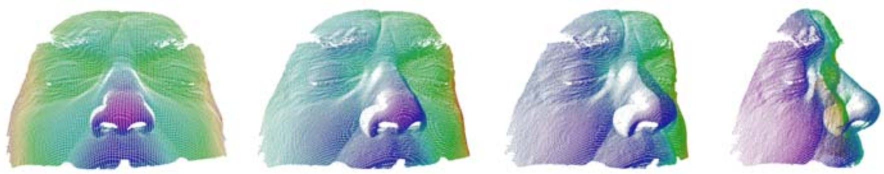

Fig. 2 Laser surface scan of the face, displayed from various view.

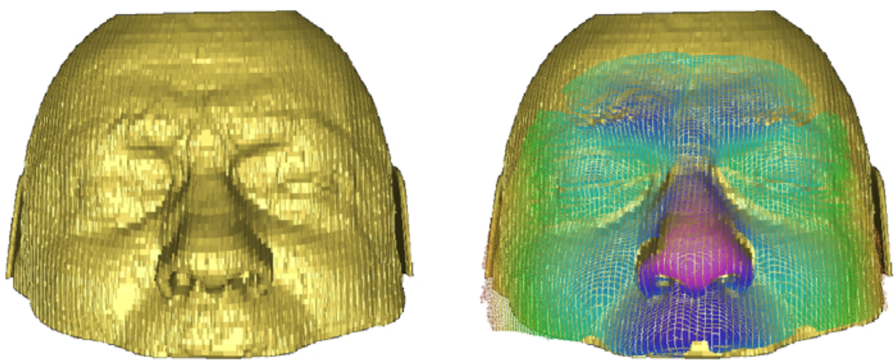

Fig. 3 Surface reconstruction of facial soft tissue from CT data (left), with laser surface scan superimposed (right).

Fig. 4 Laser surface scan of the maxilla, displayed from various views.

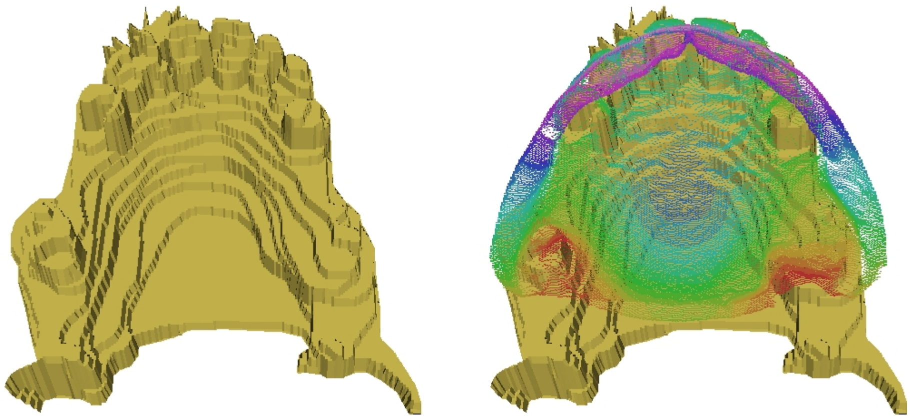

Fig. 5 Surface reconstruction of maxilla and dentition from CT data (left), with laser surface scan superimposed (right).

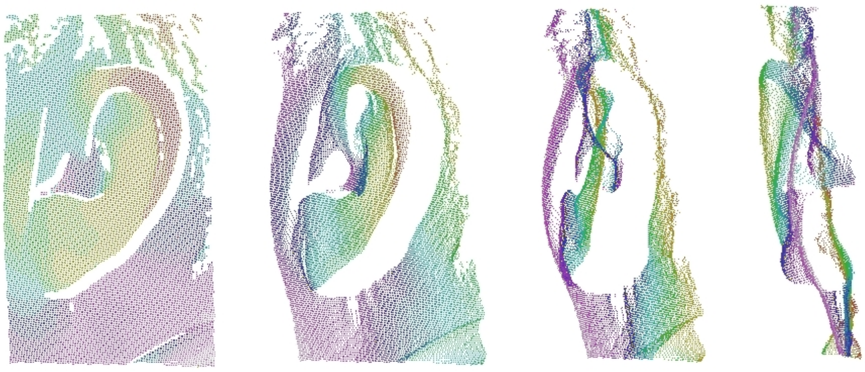

Fig. 6 Laser surface scan of the auricle, displayed from various views.

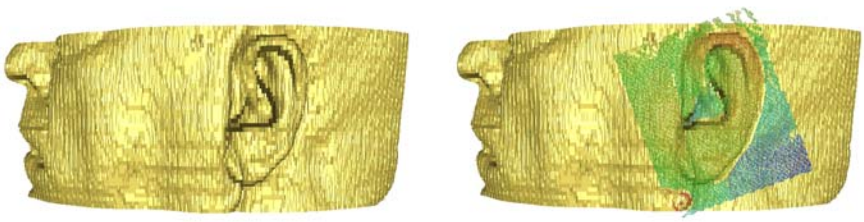

Fig. 7 Surface reconstruction of auricular soft tissue from CT data (left), with laser surface scan superimposed (right).

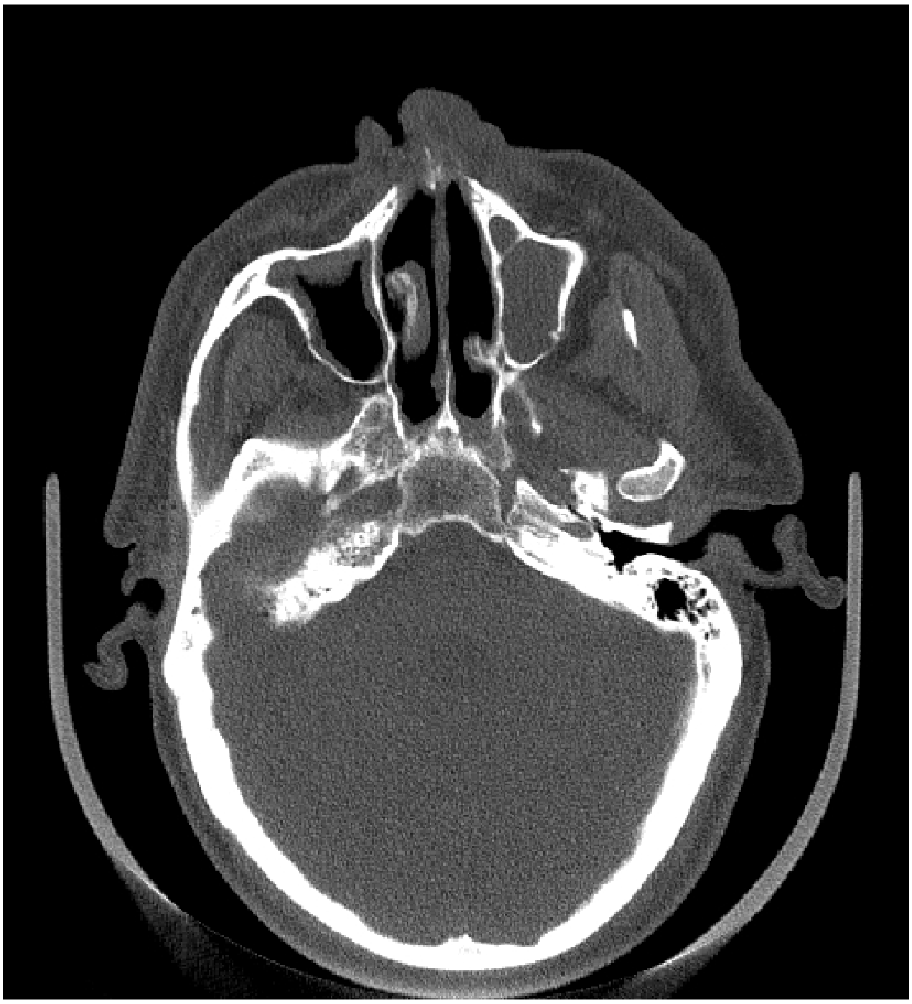

Fig. 8 Axial CT scan of the head. The left auricle is deformed by the headrest.