Non-invasive registration in computer assisted craniomaxillofacial surgery


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1. Objective

Computer-assisted technology was initially developed to provide neurosurgeons with precise guidance during surgical procedures. Currently available systems with and without robotic navigation are in use for specific medical indications. Various intraoperative navigation systems are used assisting surgery of the head and neck, such as endoscopic treatment of skull base [Kr96] and paranasal sinuses [An97], surgical corrections of posttraumatic deformities [MN98], orbital [KWM93], and orthognathic [Be96] surgery. The accuracy of electromagnetic, mechanical and optic systems has been investigated under laboratory conditions [Ro95] and seems to be sufficient especially in optical systems (0.1 mm). But under clinical conditions the accuracy of any navigation system mainly depends on the used referencing markers and the tracking system.

Registration systems with noninvasive markers (skin marker, soft tissue based frames and anatomical landmarks) are insufficiently precise and/or interfere with surgical procedures [VG99]. Other systems require invasive marker application (bone screws) before data acquisition or additional templates (e.g. stereolithographically generated) have to be performed.

Navigation of bone segments [Be96, MN98] with infrared transmitters fixed intraoperatively to the patient shows sufficient accuracy but has its limitation by using a bulky dynamic reference frame fixed to the bone segments. Furthermore craniomaxillofacial (CMF) tumor and reconstructive surgery requires more than localization of anatomical structures, transferring osteotomy lines to a surgical site or moving large single segments. Ablative tumor surgery needs detailed and exact planning using computed tomography (CT) and/or magnetic resonance imaging (MRI) to show extension of the malignoma, define intended safety margins and point out vital structures. Adjuvant chemo- and radiotherapy whether pre-, intra- or postoperative requires the same informations. Reconstruction following tumor resection as much as reconstruction of posttraumatic orbital and periorbital deformities needs reliable
information also to choose correct type and volume of grafts and to predict the outcome [Sc99b].

Demands for navigational procedures are:

1. preoperative planning
2. simulation of surgical interventions and virtual reconstruction
3. intraoperative localization and navigation with various surgical instruments
4. postoperative control of the surgical outcome and follow up of recurrence.
5. determination of the efficiency of adjuvant chemo- or radiotherapy

The aim of this study was to evaluate the use of a new developed registration system [Sc99b] for navigational treatment in cranio-maxillofacial surgery.

2. Materials and methods

Based on a spiral CT and/or a MRI data set frameless stereotaxy was performed with an infrared positioning device (fig. 1), the Surgical Tool Navigator (STN Stryker-Leibinger).

![Fig. 1: Surgical Tool Navigator (Leibinger). The infrared LED’s of the pointer are detected by the infrared cameras. Patient’s head is fixed to a Mayfield clamp and movement is tracked by the](image-url)
dynamic reference frame (DRF). Navigational surgery under local anesthesia is possible fixing the DRF to an occlusal splint for computer assisted implant insertion with a guided drill.

A non-invasive registration system was used as shown in figure 2. The Cranial Marker Set (Leibinger) as known from its use in neuronavigation consists of a plastic male matrix pin with a gold ball (diameter 1.5 mm) inside that engages the female matrix which inner thread can be screwed to the additional outer thread of the head of a 2.0-titanium bone screw. For their use with MRI hollowed pins are available which can be filled with gadolinium. For non invasive and multiple data acquisition over a long time period these markers were fixed to an individual molded occlusal splint (poly-methylmethacrylate foil, thickness: 1.5 mm). The fixation between the occlusal splint and teeth achieved sufficient and reproducible anchoraging. Four pins had to be fixed in different axial planes with adequate distance from disturbing artefacts caused by prosthetic metal. The accuracy using the new registration system was tested for its use with CT-scans under laboratory conditions in the same situation as it appears in the operation room. The "overall-accuracy" of the system was determined, this means CT-induced [HHB99], tracking-induced (dynamic reference frame and pointer) and registration induced errors were added to one value.

Intraoperatively the patient’s head was fixed in a Mayfield-clamp. Movement of patient and operating table was tracked by the infrared transmitters of the dynamic reference frame (DRF) detected by three infrared cameras inside the stand as shown in figure 1. Registration of the patient was performed by localization of the corresponding center of the markers with the infrared pointer facilitated by changing the pins to referencing markers. After registration the occlusal splint could be removed. With the pointer the surgeon was able to localize anatomical structures or to compare structures with simulated, preplanned structures. But any other non flexible surgical instrument, e.g. biopsy tongue, drill, saw, suction and endoscope could be localized and navigated by fixing an DRF to the tool and calibrating the tip as show.

Preoperatively the data set (axial slices, distance 1 mm) was transfered into a multiplanar view (coronar, sagittal, axial and three-dimensional-reconstruction view) for precise analyzing. The new software tools achieved measurement of distance, angle and volume of any marked region. Margins could be outlined, figures could be created and screws with any diameter and length and any other implant could be simulated. Preplanning of reconstruction results in unilateral deformities was performed by mirroring the unaffected side. This procedure was performed with a new developed mirror tool [Sc99b]. With this tool the surgeon was guided through the program step by step.

Validating of the system was achieved by localizing wellknown landmarks after referencing, e.g. anatomical landmarks (incisal point, foramina) or osteosynthetic implants (center of the head of a screw). Successful referencing was declared when the pointed landmark was localized with a failure below 1 mm on the multiplanar view. Surgical procedures started only after successful referencing. Registration was repeated after any concussion caused by osteotomy or similar alteration of the system.
Simultaneous use of CT and MRI, follow up of adjuvant chemo- and radiotherapy before and/or after operation and postoperative control of the surgical interventions were performed correlating the different data sets with the markers of the occlusal splint.

3. Results

Under laboratory conditions the range of accuracy using the non-invasive registration system was 1.0 mm and showed no significant difference to registration with bone screws or combinations when navigational surgery was limited to the facial skeleton (table 1). The accuracy decreases (1.5-2.5 mm) for frameless stereotaxy in the posterior part of the skull.
Table 1: Accuracy of frameless stereotaxy with different registration systems. The markers were fixed to an occlusal splint (3, 4 and 5 markers) and to bone screws (4 markers). Additionally the combined registration with both systems (4 markers of the splint + 1 bone marker) was tested. 540 values per registration type were determined.

Computer assisted treatment was successfully performed in 52 patients (table 2). Postoperative control was performed with correlation of pre- and postoperative CT or MRI data set using the markers of the occlusal splint and one reproducible anatomic landmark. In case of preoperative adjuvant chemotherapy image correlation of data sets before and after each cycle allowed determination of efficiency of the therapy.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Number</th>
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<tbody>
<tr>
<td>Biopsies</td>
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<td>Orbit</td>
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<tr>
<td>Osteotomies</td>
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<tr>
<td>Optic nerve decompression</td>
<td>3</td>
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<tr>
<td>Oral implantation</td>
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<td>Zygomaticus fixtures</td>
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<td>Standard implants</td>
<td>2</td>
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Table 2: List of computer assisted surgical procedures using the non-invasive registration system.

Guided biopsy

A minimal invasive biopsy of a suspected tumor close to the skull base was performed through an intraoral/transnasal approach as shown in fig. 3. The suspicious tissue showed a mucocele in the sphenoid sinus, which could be totally resected preventing damaging of the hypophysial gland.
Fig. 3: Image guided biopsy (intraoperative view): the center of the cross shows the tip of the tongue close to the hypophysial gland after resection of a mucocele in the right sphenoid sinus.

Tumor resection

Resection of an anaplastic carcinoma of the maxillary sinus was performed after adjuvant chemotherapy (fig. 4). The original tumor volume was transferred to the data acquisition after chemotherapy [Sc00b]. To achieve radical resection of the tumor computer assisted surgery was performed to guarantee excision of all tissue within the non visible old margins before chemotherapy.

Fig. 4: Anaplastic carcinoma after adjuvant chemotherapy. The original tumor volume before chemotherapy (outer green margin) was transferred to the posttherapeutic data set to achieve radical resection inside the pretherapeutic margins.
Endoscopic surgery

In posttraumatic chronic infection of the paranasal sinuses navigational endoscopic surgery allows safer surgical procedures due to the anatomical changes. Fig. 5 shows the intraoperative view during endoscopic revision of the frontal sinus two years after a panfacial fracture.

![Fig. 5: Navigational endoscopic sinus surgery two years after panfacial fracture. The LED-tracked endoscope and the intraperative monitor screen are shown.](image)

Reconstructive surgery

Correction of posttraumatic defects or after radical resection of malignomas are still a surgical challenge. Using computer assisted surgery orbital, midface or skull base reconstruction with calvarian split bone grafts can be preoperatively planned and intraoperatively navigated. With the new mirror tool orbital, periorbital and midface reconstruction had been performed successfully with free and vascularized bone grafts. The new software tool achieved measurement of distance, angle and volume of any marked region. Margins could be marked, figures could be created and preplanning of reconstruction results in unilateral deformities was performed by mirroring the unaffected side. As well virtual limits for transplant positions could be marked, so that calvarian split grafts are not placed beyond these marks. Intraoperatively the native CT-data set or the modified CT-data set could be referred to, so that navigation of intraoperatively achieved reconstruction in comparison to preoperative virtual correction was possible at any step of the operation. Fig. 6 shows the correction of an posttraumatic enophthalmus and malposition of the left zygoma.
Fig. 6: Planning, simulation and postoperative control of secondary midface reconstruction. Malposition of left orbit and zygoma was corrected.

Orthognathic surgery

Bimaxillary osteotomies or distraction of the facial skeleton in case of severe deformities or malformations need detailed and exact planning. In craniomaxillofacial surgery advances in imaging techniques (spiral-CT, 3D-imaging) and associated technologies (stereolithographic models, CAD/CAM) have led to improved preoperative planning. Stereolithography models however do not fulfill the requirements for complex cranio-maxillofacial plastic and reconstructive procedures i.e. preoperative planning with virtual correction, intraoperative navigation and postoperative control.

Fig. 7 shows the use of computer assisted treatment in midface distraction. Preoperative planning including positioning of the distraction devices, navigational control of the osteotomy and postoperative control are demonstrated.
Fig. 7: Computer assisted distraction using preoperative planning, intraoperative navigation (positionning of the devices and navigational Le-Fort-III osteotomy) and postoperative control.

Optic nerve decompression

Decompression of the optic nerve wether postraumatic (fig. 8) or in oncologic cases still means a surgical challenge. The complex anatomy due to pathological changes achieve best conditions for the surgical success in saving patient’s vision. There also is a need for objective measurement of vision pre-, intra- and postoperatively. Microscopical and endoscopical surgical procedures can be performed with intraoperative navigation of the focus of the microscope or the tip of an endoscope. Additionally visual evoked potentials can be measured at any point of the treatment to find the indication, to control intraoperative changes and to achieve valid postoperative follow up.

Fig. 8: Posttraumatic decompression of the optic nerve. The focus of the microscope is correlated to the multiplanar view to prevent damaging ot the optic nerve during decompression procedure.
Oral implantation

Installation of fixtures for prosthetic reconstruction in the upper jaw in patients with extensive bone and soft tissue defects indisputably is still a challenge. These situations usually require the support of vascularized bone or composit grafts and secondary insertion of endosseous implants. The zygomaticus fixture (Brånemark System) provides additional support in the above described situations by anchoring implants in the zygomatic bone. In these demanding situations preoperative planning and intraoperative monitoring of the navigational guided position of zygomaticus fixtures after subtotal maxillectomy seem to be a helpfull device [Sc00c].

Navigational insertion of two zygomaticus fixtures into the right zygoma after unilateral maxillary resection was preoperatively planned and intraoperatively navigated (fig. 9). The patient underwent resection of the posterior part of the right maxilla due to an ossifying fibroma. The template for implant insertion was armed with four CT-markers, which can be detected in the commuted tomography images. Prosthotodontic reconstruction without removable prosthesis was planned preoperatively with two zygomatic implants and one standard oral implant, which should anchore in the palatal bone. Intraoperatively drilling was computer assisted navigated to guarantee precise and parallel insertion of the two zygomaticus fixtures into the right malar bone. The postoperative panoramic view demonstrates parallel inserted zygomaticus fixtures, which achieve permanent prosthetic restauration without additional bone grafting.

With the above described new technique navigational implant insertion was also possible under local anesthesia. Tracking of patient’s mandible can be performed fixing the DRF to an occlusal splint during surgical procedure. This technique allows navigational surgery in partial edentulous patients.

Fig. 9: Computer assisted insertion of two zygomatic implants. In the intraoperative view the center of the cross shows the tip of the drill, the dotted line shows the angulation of the drill. Postoperative X-ray and clinical view are shown below.
4. Discussion

In accordance to other groups [HM98, MN99] intraoperative navigation makes radical tumor surgery more reliable by identifying the safety margins, vital structures and leading primary reconstruction to the preoperative situs. To our knowledge the non-invasive registration using the occlusal splint allows for the first time multiple data acquisition with CT and MRI in the same patient over a long period. Our registration system improves preoperative analysis by combining CT and MRI data for valid 3D visualization of the anatomic situs. Pre- and posttherapeutic tumor volume after chemo- or radiotherapy can be assessed precisely. This enables determination of the efficiency of adjuvant therapies, quick transfer of pretherapeutic tumor margins and valid postoperative follow up and detection of recurrence. The patient is able to apply the occlusal splint without any assistance and each of these data sets can be used for intraoperative navigation. The laboratory study showed sufficient accuracy (1 mm) which is comparable to markers fixed to bone screws. With this registration system navigational surgery of the facial skeleton becomes a reliable surgical tool. However some restrictions have to be remarked. The accuracy of this system refers only to the usage of the pointer with CT scans, the accuracy using MRI scans or other tools like drill, saw, chisel and endoscope has to be the interest of further investigations.

In secondary reconstruction cases the needed size and shape of the graft can be assessed preoperatively and its position can be controlled precisely during the operation. In contrary to computer assisted procedures using the Surgical Segment Navigator [MN99] no additional surface pattern is needed and online tracking with the original and virtual CT data set is possible. The mirror tool allows simulation of the intended reconstructive outcome in unilateral defects or deformities by mirroring the unaffected side of the facial skeleton. Stereolithographic models therefore become dispensable. But further developments are needed to achieve individual reconstructive planning with simulation of all kinds of segment positioning using the native CT scan not only for preoperative planning but also intraoperative navigation. This tool then will distinctively improve navigational orthognathic surgery. The safety of minimal invasive surgical procedures such as endoscopic surgery for the paranasal sinuses or skull base surgery, biopsies of suspected tumors and radical tumor resection through an intraoral approach is simplified by intraoperative navigation [Sc00a]. In optic nerve decompression the system was highly applicable as a diagnostic and surgical tool, so that transethmoidal optic nerve decompression proved to be a straight forward and safe procedure. The benefit of computer assisted treatment is evident in craniofacial surgery, traumatology, orthognathic surgery and intra- and extraoral implantation. The accuracy of navigational treatment depends mainly on the registration system. The gold standard for registration procedures can be devied in two parts. Edentulous patients need invasive bone markers for sufficient accuracy during surgery. All other patients benefit from the non-invasive registration system, the new developed occlusal splint system. The advantages are multiple non-invasive use in the same patient and the possibility for navigational surgery under local anesthesia.
References


