A-Mode Ultrasound–Based Registration in Computer-Aided Surgery of the Skull

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Objective: To evaluate the integration and accuracy of A (amplitude)-mode ultrasound–based surface matching for noninvasive registration of the head into a frameless computer-aided surgery system for otorhinology and skull base surgery.

Design: Experimental study and case series.

Setting: Academic medical center.

Patients: Twelve patients underwent anterior and paranasal skull base surgery with the routine use of a computer-aided surgery system.

Interventions: A computer-aided surgery system, based on an optoelectronic localizer, was used to track the skull and the surgical tools, including the A-mode ultrasound probe. The A-mode probe was a 10-MHz immersion transducer. An acoustic lens attached to the transducer focused the ultrasonic beam to a depth of 1 to 10 mm. Accuracy tests were performed for the ultrasound setup. Different surface point distributions were evaluated with respect to matching accuracy on a human cadaver skull specimen equipped with fiducial markers. The matching comparison was based on the fiducial registration error. For the clinical evaluation, the laboratory setup was transferred to the operating room.

Main Outcome Measures: Noninvasive registration of the skull by using A-mode ultrasound in computer-aided surgery (practical and clinical measurements).

Results: The accuracy tests on the human skull specimen revealed that the mean ± SD fiducial registration error was 1.00 ± 0.19 mm in the best series for A-mode ultrasound surface matchings and was robust with respect to different sets of surface points. The mean ± SD root mean square error from the 12 A-mode ultrasound matchings in the patient study was 0.49 ± 0.20 mm.

Conclusion: A-mode ultrasound surface matching can be used as a noninvasive and accurate registration procedure in computer-aided surgery of the head.


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A prerequisite for displaying the instruments in a virtual environment reconstructed from the acquired medical images is the establishment of a mapping between the virtual space and the surgical object. The procedure that defines such a mapping is called registration. Intraoperatively, we usually perform a 2-step registration procedure. First, several anatomic landmarks that have been defined during preoperative planning on the CT images are digitized by a physical pointer. By minimizing the least squares deviation between planned and digitized landmarks, a first alignment is performed. If bone surface exposure must be minimized or completely avoided, then only a few landmarks are available. We currently use the anterior nasal spine (A-point), the left and right frontozygomatic sutures, and the frontonasal suture (nasion) as landmarks for paranasal sinus surgery. The pointing device has limited accuracy for localizing these landmarks intraoperatively. Therefore, the first step is an efficient but rough initial alignment. This initial alignment is used as a starting point for the second step, in which the final alignment is made. An additional 12 to 20 points on the surface of the skull are digitized. The algorithm then iteratively adjusts the alignment such that the mean of the distance of each of these points to the bone surface is minimized. In the second step, there is no set of predefined landmarks corresponding to the digitized points. The first step is denoted by the term paired-points matching (PPM) and the second by surface matching (SM).

Highly accurate PPMs are possible by using extrinsic markers such as titanium screws instead of the intrinsic anatomic landmarks. Such markers can be located precisely in the image space and in real space. Extrinsic marker screws, which must be put in place under local anesthesia before CT image acquisition, are not desirable for routine surgery in otorhinolaryngology. However, they can provide a gold standard to which other matchings can be compared in an experimental laboratory setup. Adhesive labels used on the skin surface of patients are only moderately accurate markers because the labels can shift and the turgor of the skin can change.

To reach high accuracy in PPM and SM, the bone surface must be located via a navigated pointing device. Use of such a pointing device requires surgical exposure of the bone surface. This is not desirable because of the additional trauma and time requirement, unless it is otherwise part of the surgery. To minimize such trauma, we developed a transcutaneously applied needle pointer (with a 0.5-mm tip) for bone surface location.

Transcutaneous location of the bone surface by using the beam of a navigated A-mode ultrasound probe permits completely noninvasive registration. The probe is tracked by the localizer and is seen in a virtual display using the CAS system. Similar to vascular Doppler, the probe is brought in contact with the skin by using a coupling gel. Short pulses of ultrasound are transmitted into the tissue. Differences in acoustic impedance give rise to reflections in the tissue. At the soft tissue–bone interface, the complete power of the incident beam is reflected because of the high impedance difference. The echoes are received at the transducer and amplified by the receiver. If amplification of the signal is time-gain compensated, then the effect of the depth-dependent attenuation on the echo amplitude can be lowered. The probe works as a range sensor, measuring the distance from the surface of the skin to the underlying bone. The spatial position of the probe and of the ultrasound beam axis is determined by the navigation system. Distance along the x-, y-, and z-axes from the probe tip to the bone surface were added to the location of the probe to register the location of the underlying bony anatomy. Figure 1 summarizes the principle of registering bone surface points by using a pointer, a needle pointer, and an A-mode ultrasound probe.

We hypothesize that registration of the head for CAS is possible by using A-mode ultrasound, thus providing a noninvasive registration method with an accuracy that is comparable to the existing semi-invasive registration methods by needle pointer as reported in the literature. The accuracy of the SM might depend on the number and distribution of digitized bone surface points.

**METHODS**

An A-mode ultrasound probe, including its powering pulser/receiver unit and a personal computer with hardware and software, was added to an existing CAS system. To determine whether the number and distribution of digitized points affected the matching accuracy, matchings with different point sets were performed on a cadaver skull. In 12 patients undergoing CAS of the head, SM was performed by A-mode ultrasound to evaluate the feasibility of using the procedure intraoperatively.

Informed consent was obtained from every patient. The study was classified as exempt by the local institutional review board.

**CAS SYSTEM**

The CAS system was developed by our research group in Bern and is in routine clinical use (SurgiGATE ORL 3.1; Medivation/Synthes-Stratec Inc, Oberdorf, Switzerland). The tracking system is based on an optoelectronic camera (Optotrak 3020; Northern Digital Inc, Waterloo, Ontario) and allows the determination of the position of up to 256 pulsed IREDs. Image data were collected from a spiral CT scanner (LightSpeed multiscan 500 PS; General Electric Medical Systems, Milwaukee, Wis) at 1-mm collimation and 2:1 pitch in the axial plane, and a stack of 1.25-mm distant axial images was reconstructed. For image processing, segmentation, 3-dimensional (3-D) modeling, and preoperative planning, the data were transferred to a computer workstation running the CAS system (UltraSPARC 143 MHz; Sun Microsystems Inc, Palo Alto, Calif). The instrument used for PPM was a needle pointer with a 0.5-mm tip (Figure 2).

**A-MODE ULTRASOUND SYSTEM**

We used a 10-MHz ultrasonic immersion transducer measuring 12.7 mm in diameter (Phoenix ISL, Warrington, England) equipped with a DRB carrying 4 IREDs. An axicon acoustic lens focusing the ultrasonic beam in 1- to 10-mm depth with a footprint diameter of 5 mm was attached to the transducer (Figure 3). For acoustic coupling of the lens to the patient’s tissue, gel was applied (Parker Laboratories Inc, Fairfield, NJ). The transducer was activated with pulses of 200 to 400 V from an ultrasonic pulser/receiver unit (model DPR-35G; Sonix Inc, Springfield, Va). To acquire the signal, a personal computer (Pentium II processor, 160 MHz; Intel Corp, Santa Clara, Calif) was
The system unit (G) processes the position measurements that it receives from the optoelectronic camera (H) and delivers them to the CAS workstation (I). The A-mode ultrasound probe (E) is connected to the pulser/receiver (J), which is connected to the personal computer (K), which is equipped with the time-gain compensation board and the analog-to-digital converter board and runs software for signal processing and control of the pulser/receiver. The signal-processing output is echo depth and additional variables, such as echo quality. This output is transmitted to the CAS workstation via a network connection. The CAS system synchronizes and combines the position measurement from the optoelectronic camera and the echo depth from the ultrasound probe to compute the bone surface points.

**Figure 1.** Overview of the computer-aided surgery (CAS) system. A dynamic reference base equipped with infrared light-emitting diodes (IREDs) (B) is attached to the bone (light gray) of the surgical object (A). Additional IREDs are attached to the pointer devices that acquire bone surface points, such as the physical pointer (G), which requires exposure of the bone surface; the needle pointer (D), which pierces the soft tissue to access the bone; and the A-mode ultrasound probe (E), which allows registration of the surface noninvasively through the skin (black). The strober box (F) distributes the pulsed signal for the IREDs on the different marker shields. The system unit (G) processes the position measurements that it receives from the optoelectronic camera (H) and delivers them to the CAS workstation (I). The A-mode ultrasound probe (E) is connected to the pulser/receiver (J), which is connected to the personal computer (K), which is equipped with the time-gain compensation board and the analog-to-digital converter board and runs software for signal processing and control of the pulser/receiver. The signal-processing output is echo depth and additional variables, such as echo quality. This output is transmitted to the CAS workstation via a network connection. The CAS system synchronizes and combines the position measurement from the optoelectronic camera and the echo depth from the ultrasound probe to compute the bone surface points.

**Figure 2.** A needle pointer equipped with 4 infrared light-emitting diode markers. By piercing the skin and putting the 0.5-mm needle tip on the bone surface, a set of points is acquired for surface matching.

**Figure 3.** An A-mode ultrasound probe and a calibration unit, each equipped with 4 infrared light-emitting diode markers. Attached to the probe is a cone-shaped acoustic lens. By transcutaneously locating the bone surface, a set of points is acquired for surface matching.
nal was reflected, the sound velocity (SV) of the passed medium must be known. The ultrasound wave travels through a composition of different tissues with different SVs until it is reflected back from the surface of the bone. The typical transducer-bone distance on the frontal skull is less than 10 mm. The SVs of different biological tissues are known from the literature: skin, 1930 m/s; fat, 1450 m/s; muscle, 1600 m/s; bone, 3000 m/s; and air, 330 m/s. However, because the composition is locally different on each human body, it is not possible to determine one single precise value of SV. To establish an approximation, we measured the reflection time on a fresh porcine upper and lower leg specimen, which was obtained a few hours after death, and compared it with the physically measured distance from probe to bone to calculate a representative SV.

The system offers a variety of feedback information to the user operating the A-mode probe. The A-mode probe, together with other tools, can be displayed virtually on the CAS system. Raw and processed signals can be displayed as an amplitude time course or by M (motion)-mode–like imaging similar to that used by cardiologists for ultrasonic heart valve assessment. These signal representations are overlaid with the determined bone surface location. Because simultaneous operation of the probe and observation of a computer screen is a difficult task, acoustic feedback was implemented, giving information about bone surface presence and echo quality. If bone surface is detected, the frequency of repetition of the beep depends on the probe’s skin surface depth to the bone.

**EXPERIMENTAL PROTOCOL**

The procedure for the intraoperative A-mode ultrasound SM was established in a laboratory setup. One objective was to outline a course of action for clinical trials on patients. Note that the transducer could not be steam sterilized because of different temperature expansion coefficients of the transducer materials and heat-sensitive scaling at the piezoelectric crystal. The coupling gel applied to the patient’s skin also could not be sterilized. Therefore, the surgical field was cleaned with a disinfectant and a sterile covering was applied after the registration.

Another objective was to define a set of surface points that would deliver the most accurate registration relative to registration with a set of screws in the calvaria. A DRB was attached to the front of the bone of a human cadaver skull (provided by the Swiss Red Cross, Bern) using a screw-fixed support. Six fiducial titanium screws (model M1/20mm; Medivision/Synthes-Stratec Inc) were inserted into a single skull bone. On both sides, the screws were placed below the infraorbital foramen in the maxilla, supraorbital in the frontal bone, and near the mastoid process in the temporal bone. These screws were used for a gold standard PPM performed additionally for comparison with the proposed ultrasound matching. The positions of the screws were digitized using a special pointer with a hollow tip fitting to the spherical fiducial heads. The ultrasound matching tests included the following sets of points: a, 12 points (periorbital); b, 16 points (12 periorbital and 4 maxillary); c, 16 points (12 periorbital, 2 maxillary, and 2 on the zygomatic arch); d, 20 points (12 periorbital, 2 maxillary, 2 on the zygomatic arch, and 4 on the mastoid); and e, 30 points (14 periorbital, 6 maxillary, 6 on the zygomatic arch, and 4 on the mastoid) (Figure 4 and Figure 5). The anatomic landmarks for the initial PPM, acquired before the ultrasound-based SM as part of the proposed registration, were the nasion, the frontozygomatic sutures on both sides, and the anterior nasal spine. For each matching test, a fiducial registration error (FRE) was computed as a measure of matching accuracy. The FRE is defined as the mean of the differences between the fiducial positions of the ultrasound matching to those of the gold standard PPM:

\[
FRE = \frac{1}{n} \sum_{i=1}^{n} |X_{GS,i} - X_{US,i}|
\]

where \(n\) is the number of digitized points; \(X_{GS,i}\), the fiducial position after the gold standard registration; and \(X_{US,i}\), the fiducial position after the ultrasound registration.

The FRE measures the matching accuracy at the selected points of the head, where the fiducial markers are inserted. To be representative of the overall matching quality, the fiducial markers must be well distributed over the head. For paranasal and anterior skull base surgery, the registered bone surface points are usually taken in the frontal and maxillary regions of the skull. It might be suspected that the matching accuracy would be higher in this area than elsewhere. If so, one would expect that the FRE computed from the anterior 4 fiducial markers...
would be less than the FRE taking into account all 6 fiducial markers, including the posterior ones near the mastoid. Therefore, the FRE was measured for all 6 fiducial markers and for the 4 anterior fiducial markers only.

Another measure of matching accuracy is given by the root mean square error (RMSE), denoting the root mean of the squared distance from the digitized surface points to the virtual object fitted to these points:

$$RSME = \sqrt{\frac{1}{n} \sum_{i=1}^{n} dist_i(X_i)^2}$$

where $n$ is the number of digitized points; $X_i$, the position of each point after registration; and $dist()$, the closest distance to the bone surface. The RMSE produces less strong evidence of appropriate registration accuracy than does the FRE, because it does not give a comparison to a gold standard, but it is also available in a clinical assay in which control fiducial markers are absent.

### PATIENTS

Twelve patients underwent computer-aided endoscopic paranasal and anterior skull base surgery. Their diagnoses were recurrent polyposis ($n=9$), choanal atresia ($n=1$), cyst of crista galli ($n=1$), and melanoma ($n=1$). The bone surface points for SM were registered using A-mode ultrasound. In the first 6 patients, needle pointer registration was also performed for comparison. Otherwise, the entire procedure remained unchanged with respect to the routine CAS performed in the clinic.

The patients were first anesthetized. In 10 patients, the DRB was a dental plastic cast filled with silicon (Coltene AG, Altstatten, Switzerland) and mounted temporarily to the upper jaw, providing a noninvasive fixation and no discomfort for the patient. In 2 edentulous patients, the mold had to be further fixed by screws. The DRB itself had 2 separate IRED carriers with a total of 8 IREDS (Figure 5). Its use was mandatory because a single IRED carrier would often have been hidden from the camera by the ultrasound probe because it had to be properly aligned orthogonally to the surface of the bone. The 2-carrier DRB allowed for almost nonrestricted movement of the ultrasound probe and proved to also facilitate the use of other instruments.

After attaching the dental DRB to the upper jaw, the registration of the skull was performed using A-mode ultrasound. The RMSE computed by the CAS system was recorded for each SM. Once the matching was completed, clinical accuracy was assessed by (1) comparing the position of the anatomic landmarks that could clearly be identified in situ and on the virtual CT images or the 3-D reconstruction; (2) needle pointer digitization of selected bone surface points and visual inspection of the deviation in the virtual space; and (3) comparing in situ tool positions with corresponding positions in the virtual display.

Next, the surgical field was cleaned with disinfectant solution, the sterile covering was applied, and the surgery was begun with the endoscope and the navigation tools.

### RESULTS

For the SV, we measured a mean of 1540 m/s on the porcine leg specimen. This value was accepted for the clinical assay. It might be argued that an incorrect assumption of the SV impairs the matching accuracy. However, the measured depth depends linearly on the SV, and typically for registration of the head the distance is less than 10 mm. Thus, the expected SV ranges from 1500 to 1600 m/s, which corresponds to a maximum difference in distance of 0.7 mm. This is on the same order of magnitude as the resolution of the distance map used for the SM algorithm.

The SM results for the 5 different point sets that were tested on the cadaver skull are summarized in Figure 6. The mean ± SD FRE values for 6 markers and 4 markers, respectively, were 1.36 ± 0.44 mm and 1.27 ± 0.29 mm.


The use of a CAS system for open, endoscopic, or microscopic surgeries of the anterior and paranasal or lateral skull base has been a routine clinical practice in our department for more than 4 years. Registration is a crucial step in the use of a CAS system. The most desirable method is one that is fast, accurate, and noninvasive; does not require extensive training of the surgeon; and adds low costs to the price of the system.

For registration of the skull in otorhinology, different technical approaches have been realized and are in clinical use. A large class of systems is based on fiducial markers that are implanted into the bone, affixed to the skin, or are reference points on head holders. The patient must be equipped with the markers before acquisition of the CT images, and the preoperative registration can only be precise if the markers are in identical positions. Examples of systems that currently use such an approach are Smarter Vision (Stryker Leibinger GmbH, Freiburg, Germany), InstaTRAK (General Electric Medical Systems), and STN (SNN, Aalen, Germany).

In other systems, the skin surface is scanned using a contour laser for registration without markers for the CT image acquisition. Surface scanning is a fast and automated process, but it provides only indirect registration of the bone that underlies the soft tissue. Therefore, its accuracy is limited by deformation and turgor changes of the soft tissue. Systems that use this approach are, for example, Vectorvision ENT (BrainLAB AG, Munich, Germany) and Landmarx ENT (Medtronic Inc, Louisville, Colo), with the respective contour lasers z-touch (BrainLAB AG) and fazer (Medtronic Inc). Raabe et al reported a mean ± SD application accuracy in the surgical field of 2.4 ± 1.7 mm.

The CAS system in clinical use in Bern works with a needle pointer. For PPM, a brief step is needed at the beginning of the operation on the anesthetized patient to define the anatomic landmarks corresponding to the planned points on the acquired CT image. Piercing the skin, the calibrated tip of the needle is placed on the surface of the bone to collect the points. Needle pointer registration provides an accuracy of 0.84 mm. The needle pointer (with a 0.5-mm tip) thus provides accurate and fast PPM and SM without scarring, but it is a seminvasive tool.

Ultrasound provides a fast, noninvasive, and accurate way to locate the surface of the bone. Imaging ultrasonics has found widespread use in clinical medicine, including otorhinolaryngology, and a considerable amount of research has been done to develop medical ultrasonic devices. A-mode ultrasound is used for evaluation of maxillary and frontal sinus disease. B (brightness)-mode ultrasound is mainly a soft tissue imaging method used, for example, for examination of the thyroid gland and the salivary glands and for staging lymph nodes in the case of neoplastic disease. Recently, the availability of high computer performance and tracking systems has brought 3-D ultrasound to clinics. Ultrasound is also useful for purposes other than imaging, for example, for precise measurement of skin thickness and for biomechanical assessment of soft tissue in vivo.

Investigation of ultrasound for registration in CAS focused mainly on B-mode and 3-D ultrasound performed in orthopedics and neurosurgery. Barbe et al used B-mode ultrasound to register a single plastic vertebra to a CT scan. An accuracy of greater than 0.5 mm was achieved, but segmentation and extraction of bone surface points from the ultrasonic images requires manual assistance. Ault and Siegel, on scanning the femur with a tracked B-mode probe, reconstructed a 3-D model and matched it to the CT images, but accuracy was limited, with matching errors of up to 5 mm. In neurosurgery, single ultrasound slices that are acquired intraoperatively are overlaid with the CT or magnetic resonance images to assess the brain shift that impairs stereotactic navigation.

Our approach is to use ultrasound not as an imaging means but as a range sensor to detect bone surface points directly. The principle of using ultrasound-based range sensors to detect material surfaces or interfaces of different acoustic impedance is a long-established technical solution. Examples include marine sonar or fluid...
level sensors. A medical application is the use of airborne ultrasound to measure the degree of scoliosis. A tracked A-mode ultrasound probe was used by Lewis et al. and Schreiner et al. to locate fiducial markers permanently implanted in the skull. The markers were shaped to provide optimal localization characteristics, and they showed that compared with the use of anatomic landmarks or markers applied to the skin, registration was achieved at 0.5-mm average accuracy, which meets the needs of image-guided brain surgery. Maurer et al. used a tracked A-mode probe with a water-filled plastic offset to collect bone surface points and register the skull. They reported an average accuracy of 1.0 mm for plastic skull phantoms, 3 volunteers, and 1 patient.

The A-mode ultrasound range sensor presented herein (cost, $350) can detect bone surface transcutaneously with high accuracy, and the semi-invasive needle pointer can be replaced by a conceptually similar tool. It was used successfully for noninvasive SM of the head. The ultrasound system works automatically; no user interaction other than operating the foot switch when collecting points is necessary. No fiducial markers are necessary. Registration is possible with accuracy that is appropriate for CAS systems. Because we perform the registration only immediately before the surgery on the anesthetized patient, use of a nonsterile transducer was feasible. For intraoperative matchings, the transducer could have been gas sterilized. For 16 to 30 bone surface points registered in the frontal and maxillary area, the matching results did not differ; whereas, when only 12 points were used, the accuracy was poorer. Matching accuracy was not poorer in areas farther away from the collected surface points. Accordingly, a matching performed on the frontal and maxillary area could be used for lateral skull base surgery.

The current matching algorithm was developed for physical pointing devices; therefore, it is optimized for a limited number of registered surface points. For more than 30 points, processing time is reduced to values that are not acceptable with respect to costs of the operating room. However, noninvasive methods such as A-mode ultrasound allow for the collection of many more points, presumably increasing the matching accuracy. Future work will also concentrate on the development of a matching algorithm for up to several hundred registered points.

In the system’s current form, an additional computer in the operating room was necessary. This can be avoided by implementing the ultrasound software on a digital signal-processing unit, therefore replacing the personal computer with an encapsulated module or a board for the CAS workstation.

The water-coupled acoustic lens focusing the ultrasound beam complicates handling of the probe in the operating room, and probes without acoustic lenses might be sufficient for bone surface registration. Lensless probes should be evaluated and compared with the probe used in this study.

In conclusion, a specific method for registration of the head in CAS is proposed. Registration by A-mode ultrasound is noninvasive and accurate. The method has been successfully applied in the operating room and will become a routine part of the clinical application of our CAS system.

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REFERENCES