Coregistered intraoperative ultrasonography in resection of malignant glioma

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Object. The authors present their experience with coregistration of preoperative imaging data to intraoperative ultrasonography in the resection of high-grade gliomas, focusing on methodology and clinical observation.

Methods. Images were obtained preoperatively and coregistered to intraoperative hand-held ultrasound images by merging the respective imaging coordinate systems. After patient registration and imaging calibration, the authors computed the location on the magnetic resonance (MR) space of each pixel on an ultrasound image acquired in the operating room. The data were retrospectively reviewed in 11 patients with high-grade gliomas who underwent ultrasonography-assisted resection at our institution between June 2000 and December 2002.

Satisfactory coregistration of intraoperative ultrasound and preoperative MR images was accomplished in all cases. Ultrasound and MR image data were closely congruent. Preoperative setup and intraoperative use of the system were unencumbering.

Conclusions. Based on these preliminary results, intraoperative ultrasonography is an attractive neuronavigational alternative, by which a less expensive and constraining imaging technique is used to acquire updated information. Optimal intraoperative guidance can be provided by the integration of this with other imaging studies.

KEY WORDS • coregistration • image guidance • glioma • neuronavigation • stereotaxy • ultrasonography

Modern neuronavigational technologies have a major impact on intracranial neurosurgery. Neuronavigation allows localization of the lesion, determination of its size, and determination of a safe surgical corridor by which to approach it. Different surgical navigation systems are now in use, including multiarticulated arms, optical systems, and magnetic systems, which provide different localizing techniques. All of these systems require imaging data acquired preoperatively. Intraoperative ultrasonography offers real-time data.

Coregistration of intraoperative ultrasound images is now possible using image-guided technology, and this is being implemented by a number of groups. Issues of implementation including methodology, accuracy, and evaluation of tumor remnants with high sensitivity and specificity are not well characterized.

We present our experience with coregistered ultrasound images in the resection of high-grade gliomas, with particular attention to methodology and clinical observation.

CLINICAL MATERIAL AND METHODS

Preoperative images coregistered with intraoperative hand-held ultrasound images were generated by merging several spaces defined by their respective coordinate systems. The preoperative MR imaging data set defines its own coordinate system, usually expressed in pixels (x and y) and slice number (z), which can be translated to dimensional units (in millimeters) by using information on pixel size and slice spacing obtained from the image stack header. Similarly, ultrasound images have a 2D coordinate system that is expressed in pixels or millimeters. In the operating room, an optical 3D tracker (Hybrid Polaris; Northern Digital Inc., Waterloo, ON, Canada) was used to record the position of various accessories in its working volume and defined our-world coordinate system. One light-emitting diode array was attached to the head clamp and was thus rigidly coupled to the patient’s cranium, and a second array was attached to the hand-held ultrasonographic imaging scan head. Two steps were necessary to define the transformations needed to merge the various coordinate systems in a common space: patient registration and ultrasonography imaging head calibration.

Patient Registration

Patient registration consisted of computing a rigid transformation that mapped points expressed in MR imaging coordinates into world coordinates. Fiducial markers were placed on the patient’s head to allow identification on the preoperative imaging study. Their location in MR imaging space was obtained by inspection of the images.
and initially expressed in pixels and slice numbers, and then translated to millimeters by using the correct pixel size and slice spacing. The same markers are identified on the patient in the operating room following induction of general anesthesia, and their location in world coordinates was recorded using an ultrasound imaging plane, whereas the three Points a, b, and c represent the intersections of the N arrangement of wires with the ultrasound image. Points P1 through P4 represent the location of the vertices of the N in world coordinates.

**Scanning Head Calibration**

The relative position of the scan head and the light-emitting diode array used to report its position in world coordinates needs to be defined. Each time the marker was clamped onto the scan head, the assembly was calibrated. This was performed using a dedicated tank in which metal wires described an “N” in which two wires run parallel and a third intersects them both. The purpose of the calibration was to determine a transformation matrix \( T_{ui} \) where \( T_{ui} = T_{wu} T_{ui} \). The procedure has been outlined previously.

We then merged MR imaging and patient data by using this transformation, with the patient location expressed directly in world coordinates. In our implementation, we monitored the patient’s head via the array attached to the head clamp, accounting for any motion of the patient with respect to the tracker that may have resulted from the sag of the head clamp under varying loading, or simply adjustments to the operating table intraoperatively. The fiducial points were expressed in the frame defined by the head clamp marker and their position in world coordinates computed with the rigid transformation relating patient and world frames, which was reported as follows by the 3D tracker: \( P_i = T_{wu} P_i \), where the subscripted or superscripted “w” indicates world coordinates and the subscripted “p” indicates patient coordinates.

**Coregistered Image Reconstruction**

After patient registration and image calibration, we computed the location in MR imaging space of each pixel on an ultrasound image obtained in the operating room. This involved several transformation matrices as shown in the following expression:

\[
P_{MR} = T_{pat} T_{w} T_{ui} P_{ui},
\]

where the various subscripts represent each frame of reference and correspond to the ultrasound image (ui), ultrasound tracker (ui), world (w), patient (pat), and finally MR image (MR). It should be noted that in this formulation, it is implied that the patient registration is defined for homologous points expressed in MR imaging and patient-related coordinates rather than in MR imaging and world coordinates, resulting in the transformation matrix \( T_{pat} \).

The process of reconstructing an equivalent MR image for a given arbitrarily oriented ultrasound image consisted of computing the MR imaging coordinate for each point on the ultrasound image. An obvious efficiency derived from computing the overall transformation \( MR T_{ui} = MR T_{pat} T_{w} T_{ui} \) only once. Once the coordinate transformation was computed, the pixel value corresponding to that location in MR imaging space was obtained, based on which was the nearest pixel, and the image was constructed in this manner for every pixel on the ultrasound image.

**Patient Population**

We retrospectively reviewed data obtained in 42 consecutive patients with intracranial disease in whom the senior author (D.W.R.) performed intraoperative ultrasonography-assisted tumor resection at our institution between June 2000 and December 2002. High-grade malignancy was diagnosed in 11 of these patients: GBM in eight, anaplastic astrocytoma in two, and gemistocytic astrocytoma in one. There were seven men and four woman patients, and the mean age was 55.1 years (range 35–76 years). Of the 11 tumors, six were located in the frontal lobe (three on the right, and three on the left), two in the temporal lobe (one on the right and one on the left), one in the parietal lobe, and one in the occipital lobe.
two in the left parietal lobe, and one in the right fronto-parietal region.

RESULTS

Integration of the coregistered ultrasonography system into the operating room was accomplished in all 11 cases without difficulty. Coregistration of the optical digitizer used for the ultrasonography transducer added several minutes to the setup in each case. Attention was required when positioning the additional optical digitizer cameras but this was not problematic.

In all instances the ultrasound image and reformatted MR image were recognizably of approximate congruence (Figs. 2–4). Relatively fixed intracranial structures, such as the falx, were generally within 0 to 2 mm of one another. Soft-tissue misregistration was consistently greater, and increasing discordance was observed over the duration of the operative procedures. Displacement of soft tissue by varying the ultrasonography transducer’s application pressure on the dura or brain surface was visually apparent and minimized either by contact with irrigation fluid only or particular care in transducer application.

Areas of increased signal intensity on T₁-weighted MR images, areas of contrast enhancement, and vasculature tended to correspond to areas of greatest echogenicity. The extent of tumor beyond these particular features was not more apparent on ultrasound than MR images, although further analysis of this issue continues.

DISCUSSION

Appropriate neurosurgical intervention often provides the patient with a brain tumor an improved neurological status, improved quality of life, and possibly prolonged survival. Optimal resection can be achieved when the tumor is specifically localized, the borders clearly elucidated, and any residual tumor readily identified. Intraoperative imaging modalities offer the obvious advantage of determining these factors in real time, and of these ultrasonography is widely available, relatively inexpensive, and nonconstraining. Several groups have attempted to combine intraoperative neuronavigation and ultrasonography to allow for real-time control intraoperatively.

Ultrasonography has been limited by its poor signal-to-noise ratio and its 2D, usually oblique orientation, both of which detract from its interpretability and value as an intraoperative adjunct. The integration of ultrasonography with stereotactically coregistered additional imaging, such as MR imaging, enables one to have the advantages of both modalities. Intraoperative computed tomography or MR imaging would similarly provide both real-time and highly detailed visualization, although issues of cost and imposed constraints may limit widespread adoption of such a resource-intensive approach.

In their early experience, Koivukangas, et al., demonstrated registered ultrasonography to be especially efficacious for a number of functions, including localization of a tumor, definition of its borders, differentiation of the tumor from cyst or necrosis, detection of residual tumor, and general guidance of the surgeon.

In a prospective study of 34 patients harboring metastatic tumors and 36 patients with gliomas, Hammoud, et al., compared the quality of intraoperative ultrasonography and postoperative imaging. They found that ultrasonography provided a good delineation of the tumor border in 83% of the primary gliomas and in 60% of the recurrent tumors. In patients who had previously undergone irradiation, however, tumor localization was difficult in 38% and determination of the tumor border unclear in 85%.

Tronnier, et al., compared low-field MR imaging and a prototype of a 3D navigated ultrasonography to determine imaging-related quality in lesion detection and intraoperative resection control. In 70% of patients accurate tumor delineation was demonstrated prior to tumor resection. Detection of metastases and high-grade gliomas as well as intraoperative delineation of tumor remnants was comparable between both imaging modalities.

Fig. 2. Upper: Intraoperative ultrasound of a left parietal GBM in a 58-year-old woman. Center: Reformatted MR image corresponding to the ultrasonography-depicted location. Lower: Composite image with coregistered ultrasound (green) and MR image (red) data.
Various clinical and technical refinements for improving ultrasound image quality in clinical neurosurgery have been described. Unsgaard, et al.,\textsuperscript{13} described the use of a second minicraniotomy for insertion of the ultrasonography probe, ensuring optimal imaging conditions. There were no complications because of this special clinical setup, and the image quality was optimized.

Hata, et al.,\textsuperscript{6} reported using an armless intraoperative navigation system to register ultrasound to preoperative MR computerized tomography images. This system updated the preoperative image with real-time ultrasonography and offered a means to compensate for deformation of the tumor and brain resulting from operative maneuvers.

A simultaneous display of corresponding 3D-derived MR imaging and ultrasonography slices enables the surgeon to interpret information more easily on the updated ultrasound images. This observation was made by early investigators of this technique, including Trobaugh, et al.\textsuperscript{11} There are several display techniques with the potential to improve the user friendliness of image-guided surgery. One example may be multimodal imaging by fusion of the 3D ultrasound and MR image together in one scene. An alternative display technique may be stereoscopic interfaces used in combination with ordinary slicing techniques to improve the understanding and perception of complex 3D structures during surgery.\textsuperscript{2} All available and potentially helpful preoperative MR imaging data, including functional MR imaging, may be fused with intraoperative real-time 3D ultrasound images and integrated into future neuronavigation systems. Incentives include increased availability of imaging modalities as well as the relatively low costs of such systems compared with alter-

Fig. 3. \textit{Upper:} Intraoperative ultrasound of a right frontoparietal recurrent GBM in a 51-year-old man. \textit{Center:} Reformatted MR image corresponding to the ultrasonography-depicted location. \textit{Lower:} Composite image with coregistered ultrasound (green) and MR image (red) data.

Fig. 4. \textit{Upper:} A different intraoperative ultrasound of the same patient as in Fig. 3. \textit{Center:} Reformatted MR image corresponding to the ultrasonography-demonstrated location. \textit{Left:} Composite image with coregistered ultrasound (green) and MR image (red) data.
Coregistered intraoperative ultrasonography

native systems approaches. New developments in more refined integration of 3D ultrasound imaging technology with navigation technology could solve the orientation problems encountered when using 2D ultrasoundography. Ultrasonography may then be used as any other 3D imaging modality in neuronavigation. Ultimately, the integration of intraoperatively acquired ultrasonography data into a computational model may enable nonrigid transformation of highly resolved preoperative MR imaging data in near real time.

CONCLUSIONS

Ultrasonography has considerable appeal as an intraoperative imaging modality principally because of its availability, affordability, limited additional constraints, and ease of use. Three-dimensional ultrasonography has the potential to become an alternative to open MR imaging as an intraoperative imaging modality in neuronavigation. We report an application of intraoperative coregistered ultrasonography used to acquire the benefits of updated information that, when integrated with other imaging studies, provides additional image guidance.

References


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