Image Updating for Brain Shift Compensation During Resection

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BACKGROUND: In open-cranial neurosurgery, preoperative magnetic resonance (pMR) images are typically coregistered for intraoperative guidance. Their accuracy can be significantly degraded by intraoperative brain deformation, especially when resection is involved.

OBJECTIVE: To produce model updated MR (uMR) images to compensate for brain shift that occurred during resection, and evaluate the performance of the image-updating process in terms of accuracy and computational efficiency.

METHODS: In 14 resection cases, intraoperative stereovision image pairs were acquired after dural opening and during resection to generate displacement maps of the surgical field. These data were assimilated by a biomechanical model to create uMR volumes of the evolving surgical field. A tracked stylus provided independent measurements of feature locations to quantify target registration errors (TREs) in the original coregistered pMR and uMR as surgery progressed.

RESULTS: Updated MR TREs were 1.66 ± 0.27 and 1.92 ± 0.49 mm in the 14 cases after dural opening and after partial resection, respectively, compared to 8.48 ± 3.74 and 8.77 ± 4.61 mm for pMR, respectively. The overall computational time for generating uMRs after partial resection was less than 10 min.

CONCLUSION: We have developed an image-updating system to compensate for brain deformation during resection using a computational model with data assimilation of displacements measured with intraoperative stereovision imaging that maintains TREs less than 2 mm on average.

KEYWORDS: Brain deformation, FEM model, Image-guided neurosurgery, Intraoperative stereovision, Optical flow, Resection, Sparse data

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Preoperative magnetic resonance (pMR) images are typically used for intraoperative image guidance in open cranial surgery. Commercial navigation systems are available to rigidly align pMR with the patient's head in the operating room (OR),¹ and provide real-time navigation with an average accuracy of 2 to 5 mm.² However, coregistration can be significantly degraded by nonrigid brain deformation, especially as surgery progresses.

ABBREVIATIONS: 3-D, 3-dimensional; CCD, charge-coupled device; FEM, finite element model; iMR, intraoperative magnetic resonance; iSV, intraoperative stereovision; iUS, intraoperative ultrasound; OF, optical flow; OR, operating room; pMR, preoperative magnetic resonance; POC, percentage of correction; TRE, target registration error; uMR, updated magnetic resonance

To maintain accuracy, image-updating systems have been developed to generate updated MR (uMR) images using data-driven biomechanical models.^{3–13} Compared to intraoperative MR (iMR), model-based image updating is cost-effective and minimally disruptive to surgical workflow. As a result, the image-updating process can be repeated multiple times throughout a procedure, unlike iMR, which is typically acquired only at the presumed end of resection, because of the time and disruption involved.

In a previous work,¹⁴ we produced uMRs in the OR to compensate for brain deformation but only after dural opening. Sun et al¹⁵ used laser range scanning to account for postresection brain shift, but tumor volume was not removed to represent extent of resection. In this paper, we report extensions of our image-updating process that enable multiple (second and beyond)

TABLE 1. Summary of Patient Information

Patient	Gender	Age	Lesion	Location	Craniotomy size (cm × cm)	Registration accuracy (mm)
1	F	39	Arteriovenous Malformation	Right frontal	4.9 × 4.8	1.72
2	M	41	Oligodendroglioma	Right temporal	5.3 × 5.0	2.11
3	F	61	Meningioma	Right parietal	7.3 × 5.3	2.14
4	F	53	Epilepsy	Left temporal	7.6 × 5.6	0.98
5	F	24	Mixed oligoastrocytoma	Right parietal	6.2 × 4.4	1.18
6	F	49	Metastatic melanoma	Right temporal	3.1 × 2.6	2.38
7	M	78	Metastatic neuroendocrine carcinoma	Right occipital	7.8 × 5.8	4.82
8	F	65	Meningioma	Right temporal	5.0 × 3.9	1.84
9	M	60	Glioblastoma	Left temporal	4.6 × 3.6	1.49
10	F	51	Meningioma	Left frontal	7.8 × 5.4	1.94
11	F	59	Anaplastic mixed oligoastrocytoma	Right frontal	4.7 × 3.8	2.01
12	F	46	Meningioma	Right parietal	5.3 × 4.8	1.40
13	M	75	Glioblastoma	Left temporal	7.4 × 4.6	1.40
14	M	40	Meningioma	Left frontal	7.8 × 5.7	1.98

uMRs to be generated by incorporating optical flow (OF) motion tracking of successive intraoperative stereovision (iSV) acquisitions during resection in 14 surgeries. We also assess the accuracy of uMRs with independent measurements of feature locations in the surgical field with a tracked stylus, allowing target registration error (TRE) estimates of multiple uMRs to be generated for the first time. We report the overall computational efficiency of the processes involved. Results show that registration accuracy is significantly improved over pMR with computational efficiency that can be maintained within clinically acceptable ranges.

METHODS

Surgical Cases and Procedure

Image data from 14 patients undergoing open cranial procedures were evaluated, retrospectively. The study was approved by the Institutional Review Board and patient consent was obtained. Surgical procedures included craniotomies for tumor, epilepsy, or arteriovenous malformation. Criteria for data inclusion were (1) T1-weighted contrast-enhanced MRI acquired prior to surgery (scan size = 256×256 , 96–160 slices, voxel size = $0.9375 \text{ mm} \times 0.9375 \text{ mm} \times 1.5 \text{ mm}$); and (2) common features, such as blood vessels and sulci, visible on both MR scans and the exposed cortical surface. Subject gender, age, type of lesion, and size of craniotomy are reported in Table 1. At the time of surgery, patient registration was performed with pMR on a commercial navigation system (StealthStation® S7®, Medtronic, Louisville, Colorado) to provide standard-of-care intraoperative navigation and tracking. The reported accuracy of patient registration was 1.96 mm on average and is listed in Table 1 for each individual case. A surgical microscope (OPMI Pentero® Carl Zeiss Surgical GmbH, Oberkochen, Germany) was connected to the StealthStation® for intraoperative tracking, and an iSV system (Figure 1) was attached to and draped together with the microscope. The iSV system consisted of 2

charge-coupled device (CCD) cameras (Flea2 FL2G-50S5C, Point Grey Research, Inc, Richmond, British Columbia, Canada; image resolution: 1024×768 pixels), and was precalibrated^{16–18} and coregistered with pMR using tracking data acquired from the StealthStation® through the Medtronic StealthLink® (Medtronic, Louisville, Colorado) communications framework.

MR Image-Updating Procedure

A flowchart of the model-based image-updating process is shown in Figure 2. First, uMR was produced to compensate for brain deformation due to dural opening.¹⁴ Specifically, the brain was segmented

FIGURE 1. The iSV system (red box). Two CCD cameras (yellow arrow) were connected to an adapter that was attached to one of the optical ports on the microscope head.

from pMR using an adaptive preterm segmentation algorithm.¹⁹ After dural opening, an iSV image pair was acquired and a 3-dimensional (3-D) profile of the exposed cortical surface was reconstructed (iSV₁). A tetrahedral mesh (mesh₀) was generated with local refinement near the craniotomy, whose location and size were determined from iSV₁. Surface displacements (sparse data₁) were extracted by registering iSV₁ with pMR,²⁰ and employed to drive a biomechanical finite element model (FEM), in which the misfit between model estimates and measured displacements was minimized.²¹ The FEM model computed a whole-brain deformation field, in the form of the 3-D displacements of each node in the brain mesh. This information was then used to compute the new locations of each voxel in pMR and produce the updated MR (uMR₁).

During resection, a second iSV image pair was acquired to reconstruct a 3-D surface (iSV₂) of the current surgical field. OF registration was applied to register iSV₁ with iSV₂ to measure surface shift (sparse data₂).²² The amount of tissue removal was then estimated using an approach previously described in detail.²³ Specifically, the resection cavity on iSV₂ provided an initial estimate of tissue removal relative to uMR₁, a brain mesh (mesh₁) with a resection cavity was created, and the FEM model was executed. If the resulting brain deformation caused the resection cavity to deform further, and thus, no longer be aligned with iSV₂, a revised resection cavity was created from iSV₂ by shifting it in the opposite direction by the average model-estimated cavity shift. A new brain mesh (mesh₂) with the revised cavity was created, and the FEM model was executed again and the model-estimated

whole-brain deformation was used to deform uMR_1 and produce uMR_2 .

Data Analysis

To assess accuracy, uMR_1 and uMR_2 were first visually compared with the corresponding iSV surfaces in both 2-D and 3-D views. Furthermore, we quantified the misfit and TRE for pMR , uMR_1 , and uMR_2 , respectively. Specifically, the misfit of uMR_1 and uMR_2 was computed as the root-mean-squared error between measured displacements (determined by surface registration) and model estimates at the same locations ($\text{uMR}_1\text{-iSV}_1$ and $\text{uMR}_2\text{-iSV}_2$, respectively). The pMR-iSV_1 misfit was computed as the average measured displacements between iSV_1 and pMR , ie, sparse data₁, and the $\text{uMR}_1\text{-iSV}_2$ misfit was computed as the average measured displacements between iSV_1 and iSV_2 , ie, sparse data₂. In addition, we analyzed the displacements to study the patterns of shift due to tissue removal by decomposing the 3-D displacements (sparse data₂) into their components along and perpendicular to the surface normal, and along the direction of gravity. The percentage of correction (POC) of uMR_1 (POC_1) was calculated as $(1 - \text{uMR}_1 \text{ misfit} / \text{pMR misfit}) \times 100\%$, and the POC of uMR_2 (POC_2) was calculated as $(1 - \text{uMR}_2 \text{ misfit} / \text{uMR}_1\text{-iSV}_2 \text{ misfit}) \times 100\%$. To quantify the TRE of pMR and uMRs , we used features in the surgical field as target points. The technical details have been published previously.¹⁴ Specifically, at the time of iSV_1 acquisition, the neurosurgeon used a tracked sterile stylus probe to locate features that were visible on both the exposed cortical surface and MR scans, such as vessel junctions, and the coordinates of

FIGURE 3. Comparison of pMR and uMRs with iSV surfaces from case 1. pMR = preoperative MR images; uMR = updated MR images; iSV = intraoperative stereovision. **A**, Representative 2-D view of pMR overlaid with iSV₁ and iSV₂ (yellow and red lines, respectively). **B**, Three-dimensional view of pMR overlaid with iSV₁, white arrow points to feature misaligned. **C**, Two-dimensional view of uMR₁ at the same coronal slice location, overlaid with iSV₁ and iSV₂ (yellow and red lines, respectively). **D**, Three-dimensional view of uMR₁ overlaid with iSV₁, white arrow points to feature accurately aligned. **E**, Two-dimensional view of uMR₂ at the same coronal slice location, overlaid with iSV₂ (red line). **F**, Three-dimensional view of uMR₂ overlaid with iSV₂, white arrow points to feature accurately aligned.

these locations in MR image space (through patient registration) were stored. The same features were localized on pMR and uMR₁, respectively. The same process was repeated at the time of iSV₂ acquisition and features were localized on pMR, uMR₁, and uMR₂. TRE was computed as the distance between the intraoperatively tracked locations of these features (transformed into MR space) and their corresponding positions in the pMR or uMR image volumes.

RESULTS

Model-Updated MR Accuracy Evaluation

Figures 3 to 6 illustrate the qualitative evaluation of accuracy in 4 representative cases. Misalignments between pMR and both iSV₁ and iSV₂ indicate that pMR was not accurate at either time point. Specifically, iSV surfaces were either above or underneath the brain surface in 2-D views (image A), indicating brain bulging or sagging, and cortical features (eg, white arrows in image B) from iSV₁ were not aligned with pMR in 3-D views, denoting lateral shift. After the first model update, uMR₁ and iSV₁ (images C and D) were well aligned in terms of both

geometry (shown in 2-D) and texture (shown in 3-D), indicating favorable accuracy. After partial resection, uMR₁ was no longer accurate when compared with iSV₂ (image C), while uMR₂ (images E and F) aligned well with iSV₂ in terms of both geometry (shown in 2-D) and texture (shown in 3-D) after a second model update. Patient 11 had a third iSV acquisition after more tissue was removed, and uMR₂ served as the input for repeating the image-updating process and producing uMR₃. Figures 6G and 6H show that uMR₃ aligned well with iSV₃.

Quantitative accuracy assessments are reported in Tables 2 (misfit) and 3 (TRE). The initial misfit between pMR and iSV₁ is reported in column 2, along with its direction along the surface normal (“+” and “−” signs for outward and inward shift, respectively). The results show that the initial misfit was 8.61 ± 3.83 mm across the 14 cases, ranging from 2.72 to 16.91 mm (column 2). After model compensation, the remaining misfit of uMR₁ was 1.95 ± 0.45 mm (column 3), and the corresponding POC of the first image update was $74\% \pm 11\%$ (POC₁, column 4). The misfit between uMR₁ and iSV₂ is reported in column 5, along with its direction along the surface

normal. The results show an average shift of 8.55 ± 4.38 mm as a result of tissue removal, ranging from 3.16 to 16.89 mm, and the direction of cortical shift was inward (indicating brain collapse) in all 14 cases. Their components along the surface normal, in the lateral direction, and along gravity are reported in columns 6 to 8, respectively. After a second update, image updating accounted for $71\% \pm 14\%$ (POC₂; column 10) of the brain shift and the remaining misfit of uMR₂ was 2.08 ± 0.56 mm (column 9). The time from dural opening to partial resection (ie, the time between iSV acquisitions) is reported in the last column.

Similarly, TREs of distinct features on the exposed surgical surface are reported in Table 3. The average TRE after the first image update was 1.66 ± 0.27 mm (uMR₁-iSV₁; column 3), relative to 8.48 ± 3.74 mm for pMR (pMR-iSV₁; column 2). After the second image update, the average TRE was 1.92 ± 0.49 mm (uMR₂-iSV₂; column 6), relative to 8.77 ± 4.61 mm, if the first, but not second image update occurred (uMR₁-iSV₂; column 5). The average TRE for pMR (pMR-iSV₂; column 4) was 8.57 ± 4.67 mm.

Computational Efficiency

The computational time of first image update was 7 to 8 min on average as reported previously.¹⁴ Here, we present the time involved in generating the second update. Reconstruction of the iSV surface was completed in ~ 6 to 7 s with graphics processing unit acceleration. The OF-based iSV-iSV surface registration was finished within 20 s, and voxels within the cavity were removed from uMR₁ within 5 s. Meshing was performed within 10 s, and model computation was finished in ~ 4 min. The resection cavity was then revised within 5 s, the model computation was repeated in ~ 4 min, and uMR₁ was warped to produce uMR₂ within 15 s. Thus, the total computational time of the second image update was within 10 min.

DISCUSSION

Preoperative MR images are conventionally used to intraoperatively guide resection. Results from 14 clinical cases show that pMR was inaccurate as soon as the dura was opened, and

FIGURE 5. Comparison of pMR and uMRs with iSV surfaces from case 14. pMR = preoperative MR images; uMR = updated MR images; iSV = intraoperative stereovision. **A**, Representative 2-D view of pMR overlaid with iSV₁ and iSV₂ (yellow and red lines, respectively). **B**, Three-dimensional view of pMR overlaid with iSV₁, white arrow points to feature misaligned. **C**, Two-dimensional view of uMR₁ at the same coronal slice location, overlaid with iSV₁ and iSV₂ (yellow and red lines, respectively). **D**, Three-dimensional view of uMR₁ overlaid with iSV₁, white arrow points to feature accurately aligned. **E**, Two-dimensional view of uMR₂ at the same coronal slice location, overlaid with iSV₂ (red line). **F**, Three-dimensional view of uMR₂ overlaid with iSV₂, white arrow points to feature accurately aligned.

continued to be inaccurate during resection. Specifically, an error of >5 mm was observed in 12 of 14 surgeries (misfit, Table 2 column 2; and TRE, Table 3 column 2) after dural opening, and in 9 out of the 14 cases after partial resection (TRE, Table 3 column 4), respectively. Updated MR images produced after dural opening (uMR₁) proved to be more accurate with an average error of <2 mm (misfit, Table 2 column 3; and TRE, Table 3 column 3) and agree with results from a previous study.¹⁴ However, uMR₁ became inaccurate after tissue was removed, and further shift >5 mm (since dural opening) was observed in 10 of 14 cases (misfit, Table 2 column 5; and TRE, Table 3 column 5). After the second image update, uMR₂ proved to be more accurate than both pMR and uMR₁ with average errors ~2 mm (misfit, Table 2 column 9; and TRE, Table 3 column 6). The visual comparison between pMR/iMR and iSV does have an inherent bias because the images were clearly identifiable as either preoperative or updated, and thus, the comparison cannot be performed in a blinded fashion. The TRE was quantified by touching features on the cortical

surface with a tracked stylus and identifying them in the MR texture map, and is, therefore, subject to human and system localization and tracking errors. The quantification of model-data misfit, however, was automatic and performed free of user input, and independently of any visual comparisons.

In addition, results show that the components of shift along the surface normal (Table 2 column 6) were similar to the components along gravity (Table 2 column 8) because the gravity vectors were largely parallel with the surface normals due to patient position. The lateral shift (Table 2 column 7) was smaller than the normal/gravity component, indicating more collapse than lateral shift of the surgical surface. Analyses and comparisons between cases are challenging because lesion types and volumes varied from case to case, and iSV images were acquired with varying extents of resection. Interestingly, errors in pMR continued to degrade/accumulate after partial resection about half the time (in 7 of 14 surgeries). The magnitude of coregistration error demonstrated after dural opening and during later resection

is substantial and clinically relevant. Image-guided volumetric resections, where completeness of tumor resection has been demonstrated to be associated with improved survival,²⁴ are dependent on accuracies generally better than a few millimeter and this is only more important later in the resection.

The overall update time after partial resection was longer than the update time after dural opening, mainly due to the second model solution required to adjust the initial estimate of tissue removal. The image-updating process was not fully automated and involved personnel in the OR for data acquisition, processing, and model computation. Although user input is likely to be required, eg, for selecting regions of interest for iSV reconstruction and OF registration, the overall efficiency of image updating can be improved by graphical user interfaces, code optimization, and further automation. Nevertheless, image updating is executed on a dedicated workstation, which allows the surgeon to continue to operate during model computation. Compared to iMR, the image-updating approach is more efficient as 20 min or more are needed to acquire iMR, and the acquisition interrupts surgical workflow.

Limitations

Some limitations do exist in the study. First, the OF surface registration method relies on common features being present at both iSV acquisition time points, and is not appropriate in some cases, eg, recurrent tumor resections in which no cortical features are visible within the craniotomy. In addition, if all features in the previous iSV are lost due to significant shift and/or resection, the OF algorithm cannot be applied. As a result, iSV surfaces need to be acquired within a certain time frame, and feature tracking can be challenging towards the end of resection. In this study, we report only cases in which features sufficient for OF registration were available to illustrate the image-updating method, and the second iSV surfaces were acquired before all features were lost. If surface displacements cannot be extracted, intraoperative ultrasound (iUS) can also be used to measure displacements deeper in the brain to drive the FEM model.^{25,26} Furthermore, data from iUS can be combined with iSV, as they sample different regions of the brain and are complementary, accordingly.²⁶ In addition, coregistered iUS images can potentially be used as a way to measure ground-truth locations of internal features

TABLE 2. Summary of Misfit of pMR and uMR in 14 Patient Cases

Patient	After dural opening			After partial resection						Time (h:min)
	pMR (mm)	uMR ₁ (mm)	POC ₁	uMR ₁ (mm)	Normal (mm)	Lateral (mm)	Gravity (mm)	uMR ₂ (mm)	POC ₂	
1	6.07 ± 0.91(-)	1.96	68%	3.16 ± 1.02(-)	2.76 ± 1.32	1.20 ± 0.48	2.89 ± 1.09	1.49	53%	1:56
2	11.04 ± 0.85(+)	2.19	80%	11.69 ± 2.58(-)	11.15 ± 2.42	3.30 ± 1.47	9.33 ± 1.95	1.65	86%	2:32
3	7.25 ± 2.24(+)	1.62	78%	5.65 ± 1.48(-)	3.71 ± 1.83	4.06 ± 0.70	4.73 ± 1.42	2.03	64%	0:59
4	4.19 ± 0.69(-)	1.58	62%	8.30 ± 2.05(-)	4.37 ± 1.24	6.67 ± 2.80	6.40 ± 1.67	2.98	64%	2:16
5	13.98 ± 3.58(+)	1.81	87%	3.43 ± 1.19(-)	2.45 ± 0.88	2.20 ± 1.26	2.17 ± 0.83	1.25	64%	2:48
6	5.73 ± 0.81(+)	2.26	61%	12.83 ± 0.96(-)	11.61 ± 1.69	4.74 ± 2.29	12.30 ± 0.91	2.23	83%	1:25
7	16.91 ± 2.45(+)	2.59	85%	10.90 ± 2.92(-)	10.45 ± 3.08	2.80 ± 0.97	9.96 ± 2.13	2.43	78%	1:27
8	2.72 ± 1.02(-)	1.35	50%	14.11 ± 2.21(-)	11.86 ± 2.30	7.37 ± 1.89	13.85 ± 2.21	2.86	80%	2:17
9	6.94 ± 1.36(+)	1.75	75%	6.23 ± 0.97(-)	5.75 ± 0.86	2.29 ± 0.80	5.65 ± 0.75	1.50	76%	1:24
10	6.47 ± 0.87(-)	1.42	78%	11.22 ± 2.10(-)	7.39 ± 1.89	8.19 ± 2.22	9.78 ± 2.31	2.13	81%	2:25
11	10.12 ± 1.34(+)	1.51	85%	10.69 ± 1.39(-)	10.55 ± 1.45	1.49 ± 0.86	8.82 ± 1.31	1.94	82%	0:38
	–	–	–	3.55 ± 0.53(-)	1.54 ± 0.22	3.20 ± 0.49	1.56 ± 0.19	1.28	64%	1:04 ^a
12	9.25 ± 1.13(+)	2.69	71%	4.92 ± 1.57(-)	2.65 ± 1.56	3.68 ± 1.91	2.38 ± 1.88	2.80	43%	2:25
13	8.75 ± 2.12(+)	2.52	71%	16.89 ± 3.05(-)	15.66 ± 2.85	6.07 ± 2.15	16.12 ± 3.01	2.43	86%	2:34
14	11.12 ± 2.04(+)	2.06	81%	4.66 ± 0.74(-)	3.63 ± 0.96	2.57 ± 1.26	3.66 ± 0.78	2.14	54%	1:15
Average	8.61 ± 3.83	1.95 ± 0.45	74% ± 11%	8.55 ± 4.38	7.04 ± 4.47	3.99 ± 2.17	7.31 ± 4.56	2.08 ± 0.56	71% ± 14%	

pMR = preoperative magnetic resonance images; uMR = updated magnetic resonance images; POC = percentage of correction.

^aThe time between the first iSV (after dural opening) and the third iSV (during resection).

TABLE 3. Summary of TREs of pMR and uMR in 14 Patient Cases. The Number of Target Points is Reported in Parenthesis

Patient	After dural opening		After partial resection		
	pMR-iSV ₁	uMR ₁ -iSV ₁	pMR-iSV ₂	uMR ₁ -iSV ₂	uMR ₂ -iSV ₂
1	6.80 ± 0.97(5)	2.00 ± 0.45	7.65 ± 0.62(2)	3.58 ± 2.93	1.49 ± 0.35
2	10.10 ± 2.75(2)	1.83 ± 1.20	4.68 ± 1.24(2)	12.23 ± 0.25	1.63 ± 1.43
3	5.84 ± 1.81(4)	1.15 ± 0.35	4.16 ± 0.25(3)	4.85 ± 1.09	1.52 ± 1.66
4	4.80 ± 0.64(5)	1.38 ± 0.84	11.99 ± 1.15(4)	8.42 ± 0.37	2.52 ± 1.15
5	13.06 ± 1.54(2)	1.52 ± 0.27	10.17(1)	2.86	1.30
6	6.95 ± 1.58(4)	2.00 ± 0.28	12.75 ± 3.62(2)	13.85 ± 0.88	2.19 ± 0.43
7	16.74 ± 2.46(4)	1.36 ± 0.72	2.86(1)	9.46	1.43
8	2.92 ± 1.08(4)	1.85 ± 0.07	16.64 ± 1.66(3)	16.54 ± 1.71	2.57 ± 0.67
9	6.15 ± 0.26(2)	1.73 ± 0.16	2.22(1)	6.41	1.61
10	5.31 ± 0.98(5)	1.50 ± 0.81	13.15 ± 2.35(4)	12.24 ± 0.40	1.80 ± 1.58
11	9.77 ± 1.50(5)	1.96 ± 0.19	4.44 ± 0.73(2)	8.62 ± 0.34	1.95 ± 0.76
	–	–	3.20(1)	5.39	1.52
12	10.08 ± 1.75(2)	1.76 ± 0.65	13.09 ± 3.25(2)	6.04 ± 1.39	2.92 ± 0.12
13	8.03 ± 1.27(4)	1.81 ± 1.11	12.09 ± 1.65(2)	16.85 ± 2.31	2.25 ± 0.34
14	12.16 ± 1.07(2)	1.45 ± 0.12	9.51(1)	4.26	2.07
Average	8.48 ± 3.74	1.66 ± 0.27	8.57 ± 4.67	8.77 ± 4.61	1.92 ± 0.49

pMR = preoperative magnetic resonance images; uMR = updated magnetic resonance images; iSV = intraoperative stereovision.

independently to quantify the accuracy of uMR deeper in the brain.

CONCLUSION

In summary, we have developed methods to produce uMR images to compensate for brain deformation due to resection by incorporating data acquired from iSV. We assessed the accuracy

of uMRs qualitatively by visually comparing them against iSV surfaces, and quantitatively by calculating misfit, percentage of brain shift correction, and TRE, and compared these accuracy assessments to the corresponding values for pMR. The results show that the accuracy of uMR was ~2 mm for both image updates (after dural opening and after partial resection), whereas pMR was inaccurate at both stages. The total computational time to generate the image updates after partial resection was ~10 min,

and had minimal influence on surgical workflow. These findings suggest that the image-updating process can be applied in the OR to provide improved image guidance accuracy during tissue resection strictly with iSV as long as common image features continue to be available in the surgical field during the procedure.

Disclosures

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COMMENTS

The use of navigation for cranial neurosurgery has become widespread and relies largely on preoperative magnetic resonance imaging. Intraoperatively, however, the reliability of this modality is reduced largely by brain shift and tissue deformation. This often leaves the surgeon with questionable image guidance at the end of the procedure, when its utility is arguably at its greatest, particularly during resection of a mass lesion. Alternative intraoperative imaging modalities, including CT, MRI, and ultrasound, have been used to complement cranial navigation and compensate for the issues with relying on preoperative MR images alone.

The authors describe their use of intraoperative stereovision images to modify and update the preoperative MRI-based navigation. They demonstrate promising results, generating updated imaging data fairly quickly and accurately after dural opening and during resection. While their fusion technique is reliant on, and perhaps limited by, the pairing of consistent cortical landmarks, it may provide an alternative method for dealing with intraoperative brain shift and its detrimental effect on navigation.

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It is accepted that image-guided surgery based on a preoperative MRI scan can suffer from loss of accuracy during surgery, due to brain shift as well as tumor resection. While intraoperative MRI imaging

can compensate for these factors, iMRI is not always available and is associated with a significant financial investment on the part of the institution. Thus, other techniques which can address these issues are welcomed. The authors report their use of image processing techniques which utilize intraoperative stereoscopic imaging data to update the preoperative MRI model and thus provide continuous accurate guidance

throughout surgery. Their technique, which is more time efficient than serial intraoperative MRI image acquisition, may be useful when intraoperative MRI is not available or not feasible for other reasons.

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