

Three-dimensional Neurostereoscopy? Subjective and Objective Comparison to 2D

Authors

J. F. Fraser¹, B. Allen¹, V. K. Anand², T. H. Schwartz¹

Affiliations

¹ Department of Neurological Surgery, Weill Medical College of Cornell University, New York-Presbyterian Hospital, New York, USA

² Department of Otorhinolaryngology, Weill Medical College of Cornell University, New York-Presbyterian Hospital, New York, USA

Key words

- 3D
- endonasal
- endoscope
- stereoscopy
- three-dimensional
- transnasal
- surgical simulators

Abstract

Neuroendoscopic procedures, particularly transnasal skull-base procedures, are currently performed with 2D endoscopes that lack stereoscopic vision and depth of field. In principal, 3D vision should be preferable to the operating surgeon, but the previously existing systems have not been adopted. We evaluated a novel 3D endoscope to compare with 2D endoscopy. 33 neurosurgeons and skull-base otolaryngologists were recruited, and randomized to complete two runs of a task-based simulator paradigm using 2D and/or 3D visualization. After the two trials, each subject completed a questionnaire assessing professional demographics and preferences for visualization. The task paradigm had objec-

tive endpoints that measured speed, efficiency, and error rates. 75% of respondents preferred 3D endoscopy, and 87.5% determined that 3D visualization either somewhat or greatly helped with the assigned tasks. In the second run, subjects using 3D demonstrated a significantly higher efficiency than subjects using 2D ($p=0.04$). Subjects' speed and efficiency improved significantly when moving from 2D to 3D, and speed and efficiency improved significantly from Run 1 to Run 2 for 3D visualization. Subjective and objective outcomes support the utility of 3D visualization for neuroendoscopic techniques. Visualization that provides real-time, high-resolution binocular depth perception has a role in endoscopic skull base surgery and other neuroendoscopic procedures.

Introduction

While minimal access neuroendoscopic surgery is a rapidly growing field, adoption of new techniques is often hampered by a steep learning curve. One of the restrictions of endoscopic or endoscope-assisted surgery is the lack of binocular, or stereoscopic, vision. Monocular endoscopes and displays create a two-dimensional (2D) image which impairs depth perception and the ability to estimate size [1,2]. Particularly in neurosurgery, where procedures are performed deep in the brain through long narrow corridors, impaired depth perception can be disastrous [3]. In spite of the limitations of the 2D endoscope, neurosurgeons have been able to train their eyes, brain and hands to adapt to the lack of 3D vision. Nevertheless, it is likely that an effective high-definition 3D endoscope would improve depth perception. This improvement may be particularly important for surgeons with limited 2D endoscopy experience [4,5]. Adding binocular vision through novel 3D imaging and rendering

technology to endoscopic approaches has the potential to reduce mistakes in movement, provide more visual anatomic cues by more clearly illuminating depth relationships, and reduce learning curves for novice surgeons [6]. In spite of these obvious advantages, there has been a relative lack of exploration into 3D neuroendoscopy. In one report on four cases, 3D neuroendoscopy was successfully used as an adjunct to traditional microscopic procedures, allowing for stereoscopic visualization of structures not visible through the microscope [3].

It is possible that the previous paucity of research into 3D neuroendoscopy represents a deficiency in adequate equipment. Earlier studies comparing 2D and 3D laparoscopic techniques were limited by the imaging technology available; first generation 3D systems based on dual CCD cameras or rapidly alternating views had poor resolution and other negative effects on the surgeon's senses (e.g., headache, dizziness, disorientation) [7]. Several recent studies in the general surgery literature using improved imaging technology

Bibliography

DOI 10.1055/s-0028-1104567
Minim Invas Neurosurg 2008;
51: 1–7
© Georg Thieme Verlag KG
Stuttgart · New York
ISSN 0946-7211

Correspondence

T. H. Schwartz, MD

Department of Neurosurgery
Weill Cornell Medical Center
New York Presbyterian Hospital
525 E. 68th Street
10021 New York
USA
Tel.: +1/212/746 56 20
Fax: +1/212/746 55 92
schwartz@med.cornell.edu

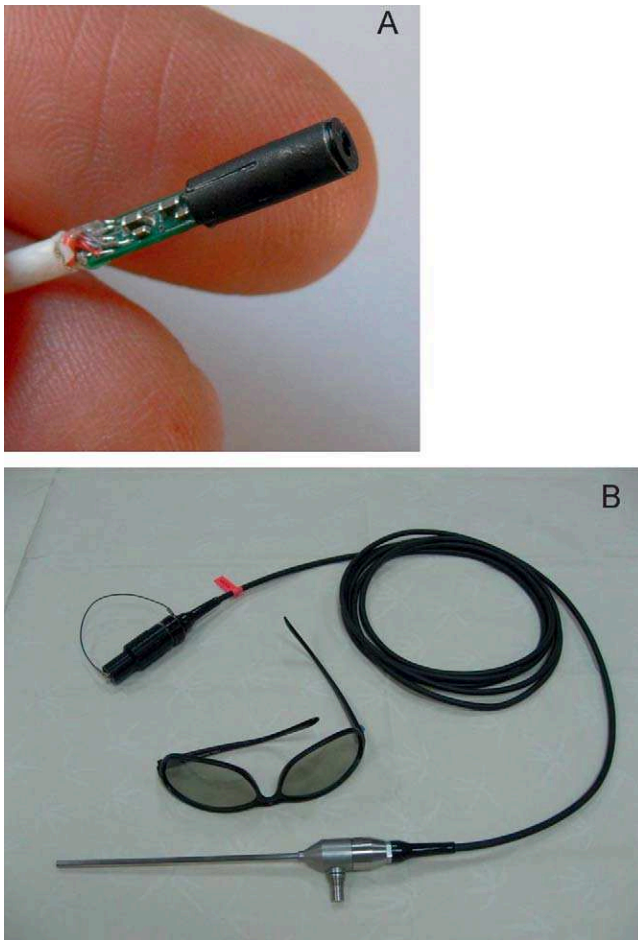


Fig. 1 A The Visionsense camera represents a micro array of lenses. B It was loaded into the tip of a straight endoscope for this study.

concluded that task time, task errors, and learning time were all decreased when 3D views were used [1,2,6]. Amid such advances, 3D endoscopy has significant potential for neurosurgical applications, especially as endoscopic techniques have been used to extend transsphenoidal approaches to reach a variety of locations throughout the anterior and mid-skull base [8–20]. In this study, we compared the view provided by a novel 3D endoscope to a traditional 2D view during the performance of a standard procedural paradigm, assessing precision, time, efficiency, and surgeon preference among a representative group of practitioners.

Methods

Endoscopic equipment and display

The Visionsense (New York, NY) endoscopic lens was used for this study (● Fig. 1). It uses technology that incorporates a microscopic array of lenses (similar to an insect's compound eye) in front of a single video chip on the end of the scope. This generates multiple small images that are then divided into simultaneous left and right images. The viewer's eyes then simultaneously pick up two slightly different images of the same object. The interpupillary distance (the separation between the two virtual eye points) is 0.8 mm. The outer diameter of the camera is 3.4 mm. The images were displayed using a Planar (Beaverton, OR) stereoscopic dual-flatscreen system, which uses

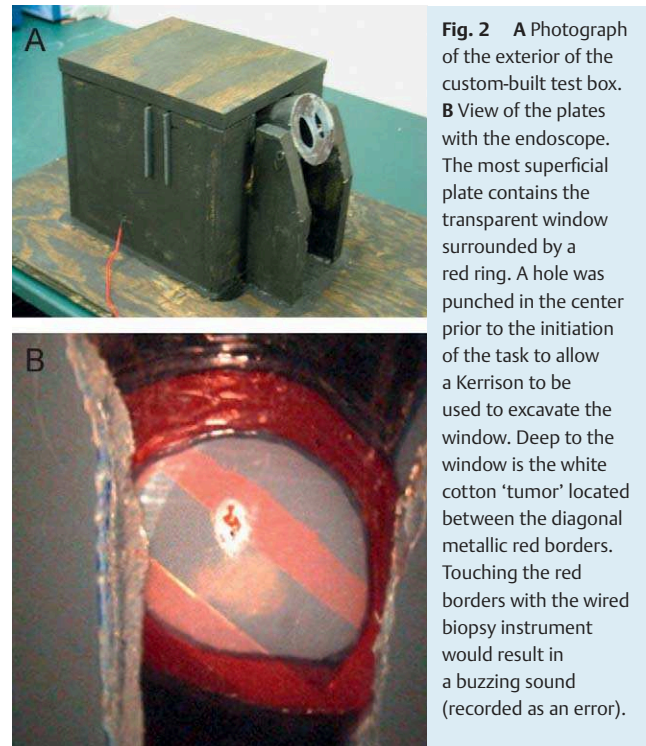


Fig. 2 A Photograph of the exterior of the custom-built test box. B View of the plates with the endoscope. The most superficial plate contains the transparent window surrounded by a red ring. A hole was punched in the center prior to the initiation of the task to allow a Kerrison to be used to excavate the window. Deep to the window is the white cotton 'tumor' located between the diagonal metallic red borders. Touching the red borders with the wired biopsy instrument would result in a buzzing sound (recorded as an error).

a coated mirror to overlay right and left images. The spatial resolution was 800×400 pixels, and the refresh rate was 50 frames per second. The depth of field is 15–70 mm, with a field of view of 70 degrees. For 2D visualization, the mirror was lifted, and a single monitor was used, while participants used the stereomirror display with polarized glasses for 3D visualization.

Simulator design

A task simulator was designed to compare 2-dimensional (2D) and 3-dimensional (3D) endoscopy. The task simulation was designed based on the following overall principles: to require visualization in several depth planes; to require the use of a number of different surgical skills with typical transnasal pituitary tools; to require only a brief time interval (1–5 min) in order to allow high throughput of subjects. Intraoperative feedback was also incorporated into the design to facilitate learning. Lastly, the simulation was designed to avoid precise resemblance to human endoscopic transnasal anatomy in order to minimize any advantage held by surgeons with significant operative experience. The simulator, or "taskbox," was constructed with readily available materials with an opening formed by PVC piping for entry of an endoscope (● Fig. 2A). The endoscope was mounted on a "scope-holder", which could be moved and then fixed in place to accommodate the preference of each participant. Additionally, the mounting of the endoscope allowed for bimanual technique since no hands were required to hold the scope. The participants were not instructed on how to use any of the provided instrumentation; an individual could also hold the scope with one hand if preferred. The site of the operative tasks included three layers, two of which were formed by sliding panels. To the most superficial panel was attached a replaceable 1/32-inch plastic sheet with a clear area outlined by a red ring (● Fig. 2B); this panel would be analogous to the sellar floor, typically removed during an endoscopic transsphenoidal case. A single, approximately 1/8-inch hole was placed in the middle of

the transparent plastic sheet prior to the start of the task. The middle panel was a metal window attached to a rotary motor and two size D batteries. This circuit was completed by a wire, which exited the taskbox and was attached to a down-angled pituitary biopsy rongeur. If the pituitary rongeur touched the metal window, the rotary motor would activate, emitting a loud buzzing sound. The borders of the window were marked in red. Finally, the inner panel contained a replaceable small cotton swab. When placed in the taskbox, the cotton swab was situated within the metal window, deep to the transparent plastic "sellar floor" (● Fig. 2B).

Each "run" of the taskbox consisted of the performance of two tasks in the same order. Subjects were timed during each task separately. Task 1 required the subject to use Kerrison rongeurs (1 mm, 1.5 mm, 2 mm, 4 mm available) to remove the a portion of the transparent "sellar floor" without removing any aspect of the red ring colored around its border. Each "bite" into the red ring was designated as a "cut error." Subjects were instructed to remove as much of the window as they determined to be necessary to gain access to the cotton swab. Task 2 required the subject to use the down-angled pituitary to take four small 'biopsies' of the cotton swab. There was no limit on the minimum size of the 'biopsy' sample. Each time the subject touched the red bor-

ders of the window, causing an audible alarm, they were marked with a "biopsy error" for that attempt.

Subject recruitment and simulation

Subjects were recruited at two separate events: a weekend course on endoscopic transnasal techniques held annually at our institution, and a single-day event at the 2007 Congress of Neurological Surgeons Annual Meeting in San Diego, California. For inclusion in the study, subjects were required to be neurosurgeons or otorhinolaryngologists in practice or in residency training. Subjects were not compensated for their participation in the study. Each subject completed two separate runs (one run=task 1 and task 2) of the taskbox. Subjects were randomized to complete the simulation in 2D first/3D second, 3D first/2D second, or 3D first/3D second. This randomization was performed to control for the learning curve likely to be present between run 1 and run 2. At the completion of the two runs, each subject completed a questionnaire to assess their level of expertise and endoscopic experience, and to determine their subjective impression of the different types of visualization (● Table 1).

Table 1 Example survey.

Stereoscopic Vision in Neuroendoscopy

Thank you for participating in our study to evaluate the efficacy of stereoscopic visualization in learning endoscopic techniques. Please answer the following questions; these data are non-identifiable, and will only be used in this study.

1) Are you a practicing neurosurgeon or otolaryngologist (completed residency training)?

Yes No

If so, for how many years have you been practicing ?

2) Have you completed a formal fellowship in endoscopy ?

Yes No

If you are currently in residency training, what is your PGY year?

3) Please estimate the number of endoscopic transnasal skull base cases in which you have participated.

0 1 – 5 5 – 10 10 – 20 >20

4) In approximately how many cases were you one of the primary surgeons (or chief resident if you are a resident)?

0 1 – 5 5 – 10 10 – 20 >20

5) Have you previously attended an endoscopic skull-base course?

Yes No

6) In testing the 2D versus 3D visualization, which method did you prefer for the required tasks?

2D 3D

7) How would you rate the impact of stereoscopic (3D) visualization on your ability to understand the relative depths of structures in the required tasks?

Greatly helped Somewhat helped Did not help Hindered

Please include any other comments that you believe would be helpful to our study.

Table 2 Previous endoscopic skull-base experience of subjects.

Range of Case Number	Total number of cases in which subject participated		Number of cases in which subject was primary surgeon	
	N	%	N	%
0	9	27.3	13	39.4
1–5	6	18.2	8	24.2
5–10	7	21.2	4	12.1
10–20	2	6.1	1	3
>20	9	27.3	7	21.2

Outcome variables and statistical analysis

Demographic variables evaluated included status as attending or resident/fellow, years in training or in practice, attendance at a transnasal endoscopy course, and completion of formal endoscopic fellowship training. Previous endoscopic transnasal experience was assessed. Post-participation visualization preference and subjective opinion of the utility of 3D visualization were also assessed.

Primary outcome variables included task 1 time, proportion of window cut, cutting efficiency (pixel²/sec) for task 1, cut errors and cut error rate (percent of subjects committing at least one error), task 2 time, maximum biopsy errors in one subject, and biopsy error rate (percent of subjects committing at least one error). Tests for statistical analysis included chi-squared (χ^2) comparisons and Fisher exact tests for contingency table data, t-tests for parametric data, Mann-Whitney tests for non-parametric data, and Wilcoxon tests for pair wise comparisons. P values less than 0.05 were considered significant for all analyses.

Results

Subject population

A total of 33 subjects was recruited. Subjects from the authors' home institution were not preferentially recruited in an attempt to restrict any institutional bias. Of the overall study population, 26 were attending neurosurgeons or otolaryngologists, while 7 were neurosurgery residents. Of the attending surgeons, the mean number of years in practice was 8.2 ± 6.8 . 1 resident and 5 attendings (40% of total) had previously attended an endoscopic skull-base course. 5 attendings (15% of total) had completed a formal endoscopic skull-base fellowship. When asked about previous experience with endoscopic skull-base operative cases, 72.8% of subjects had participated in at least one case, and 60.5% of subjects had been the primary surgeon in at least one case (Table 2). Previous endoscopic experience was evaluated as a potential confounding variable to results. The distribution of experience among attendings and among residents was not significantly different ($\chi^2 = 5.27$, $p = 0.26$). The distribution of randomization to visualization order groups is summarized in Table 3. A total of 15 subjects performed the first run with 2D visualization, while 18 subjects started with 3D visualization. In comparing the subgroup that performed the tasks in a 2D first, 3D second (2D/3D) order versus those that performed the task in a 3D first, 2D second (3D/2D) order, there was no statistical difference in distribution of experience ($\chi^2 = 1.68$, $p = 0.79$).

Qualitative assessment

Subjective assessment of different visualization techniques was analyzed using the post-task questionnaire. 75% of subjects preferred 3D visualization (Fig. 3A). 87.5% of subjects believed the use of 3D visualization helped with task completion to some

Table 3 Distribution of visualization order.

Vision Order	N	%
2D–3D	15	45.5
3D–2D	13	39.4
3D–3D	4	12.1
3D	1	3

degree (Fig. 3B). Of the 6 subjects who indicated a preference for 2D visualization, 2 admitted that the use of 3D visualization "somewhat helped" with task completion. Additionally, 2 of the subjects who preferred 2D visualization stated that they had difficulty adjusting to the 3D rendering and display. Results of the qualitative assessment were not affected by the vision order (2D/3D vs. 3D/2D).

Quantitative assessment

The results of the primary endpoints are summarized in Table 4. Intra-run comparisons of 2D and 3D demonstrated no significant differences in cutting efficiency or errors in run 1. However, the maximum number of errors committed by one subject in run 1 was 14 for the 2D group and 5 for the 3D group. In run 2, the 3D group demonstrated a significantly higher cutting efficiency (498 ± 239 pixel²/sec) than the 2D group (369 ± 285 pixel²/sec; $p = 0.04$). Additionally, the 2D group continued to show a higher number of maximum errors within one subject (7 versus 2). Of note, the subjects that committed 14 errors in run 1 and 7 errors in run 2 were not the same individual.

Task learning was assessed through multiple modalities. First, errors made in the first and last biopsy attempts in run 1 were compared. All subjects either committed zero errors in both first and last attempts, or reduced the number of errors from attempt one to four. However, in pair wise comparisons, while there was no difference in errors among users of 2D visualization, there was a significant reduction in errors among users of 3D visualization from the first to last attempts ($p = 0.004$; Fig. 4A,B).

Learning was also assessed by inter-run comparison of 2D and 3D separately. The statistical question asked was: Is there a difference in primary endpoints between those that used a specific visualization in the first or second run? In other words, did familiarity with the set of tasks change the objective outcomes associated with a particular type of visualization? Table 5 summarizes these outcomes. For 2D visualization, there were no significant differences between those using 2D first or second. For 3D visualization, there were significant differences in task 1 time and in cutting efficiency. This analysis was undertaken twice, with those using 3D twice (3D/3D) included and excluded. The results of the 3D/3D group had no effect on these comparisons. Finally, learning was assessed by direct within subject inter-run pair wise comparisons. Comparisons are summarized in Table 6. Task 1 time improved in both groups. For 3D/2D

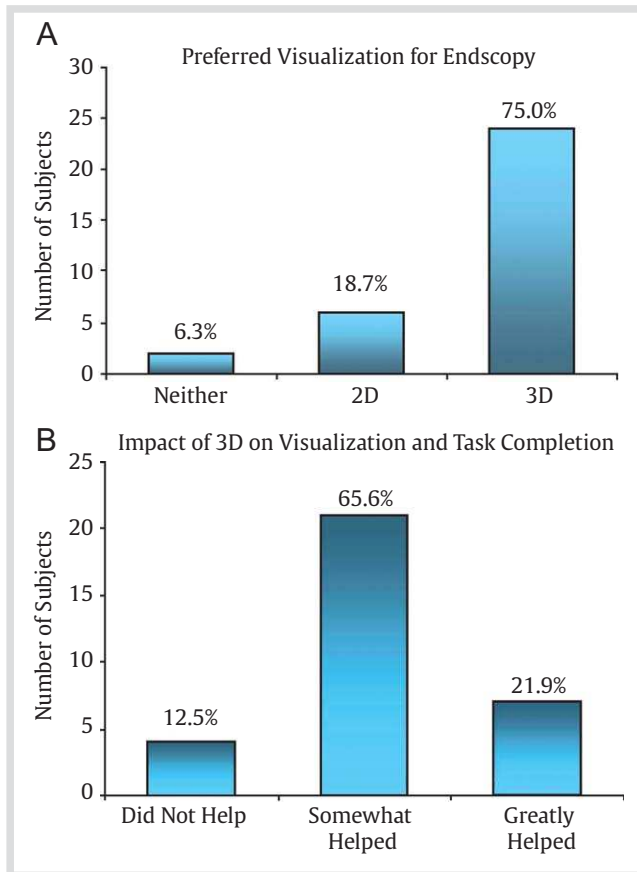


Fig. 3 Graphs demonstrating results of the qualitative assessment; the majority of subjects preferred 3D endoscopic visualization (A), and affirmed that 3D endoscopy either somewhat or greatly helped (B) with completion of the task.

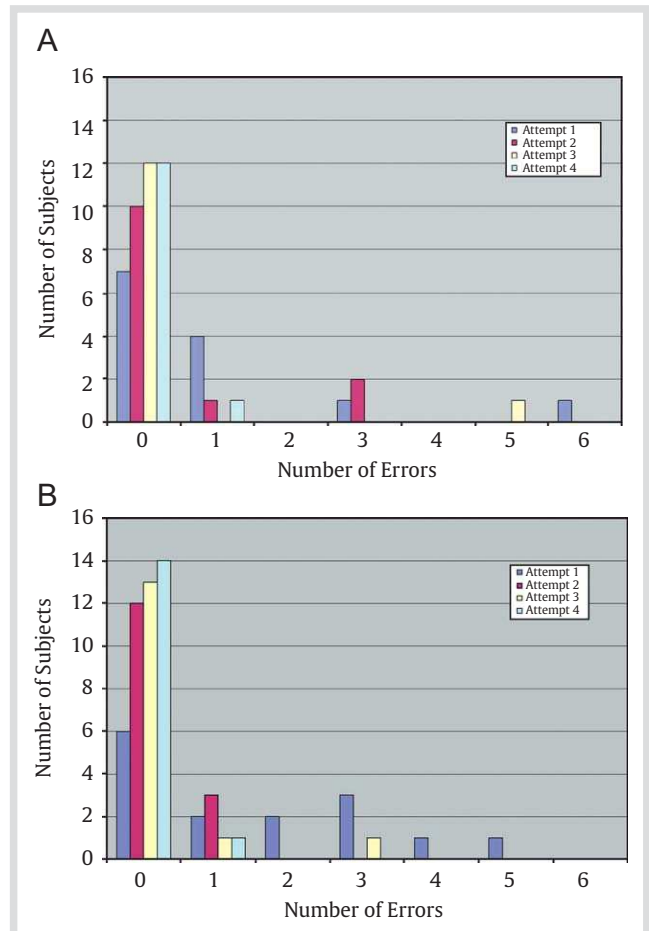


Fig. 4 Bar graphs demonstrating distribution of number of biopsy errors graphed by attempt in run 1 for 2D (A) and 3D (B) endoscopy.

Table 4 Primary Endpoints (intra-run comparison).

Run 1	Run 1			p	Run 2	Run 2		
	2D	3D				2D	3D	p
task 1 time (sec)	132 ± 70	151 ± 92	ns	task 1 time (sec)	125 ± 111	87 ± 39	ns	
proportion of window cut (%)	25.1 ± 17.2	20.1 ± 15.6	ns	proportion of window cut (%)	17.8 ± 15.4	22.1 ± 16.4	ns	
cutting efficiency (pixel ² /sec)	401 ± 182	303 ± 191	ns	cutting efficiency (pixel ² /sec)	369 ± 285	498 ± 239	0.04	
cut errors – total	5	1		cut errors – total	1	0		
cut error rate (%)	26.7	5.6	ns	cut error rate (%)	7.7	0	ns	
task 2 time (sec)	45 ± 24	53 ± 20	ns	task 2 time (sec)	48 ± 22	45 ± 25	ns	
maximum errors in one subject	14	5		maximum errors in one subject	7	2		
error rate*	61.5	66.7	ns	error rate*	54.5	50	ns	

*Defined as the percentage of subjects making ≥1 error

subjects, the median difference between run 1 (3D) and run 2 (2D) was 41.5 sec (95% confidence interval 9–76.5 s). For 2D/3D subjects, the median difference between run 1 (3D) and run 2 (2D) was 31.5 s (95% confidence interval 14–60 s).

Discussion

Neuroendoscopy is becoming an increasingly valuable tool in the armamentarium of the skull base surgeon. Its use, however, requires clear visualization, and technologies that improve endoscopic imaging are particularly vital. Three-dimensional visualization is not novel in neurosurgery. Indeed, 3D displays and

virtual reality simulators have been used as training and preparation tools for complex intracranial cases [21–23]. Additionally, prior 3D endoscopic systems have been qualitatively evaluated for use in neurosurgical cases [3]. With such a precedent, we endeavored to evaluate a new high-resolution 3D endoscopic visualization tool in a controlled experiment. Our primary qualitative assessment demonstrated a profound preference by the surgeons for 3D over 2D visualization. Importantly, no subject indicated that 3D visualization hindered the performance of the tasks; 87.5% of subjects indicated that using 3D helped their performance and visualization. While the results from the subjective assessment were profound, the objective endpoints were not as definitive. While most end-

Table 5 Learning Curve Assessed By Inter-Run, Inter-Subject Comparison.

2D	3D (3D-3D included in Run 2)			3D (3D-3D Excluded in Run 2)							
	Run 1	Run 2	p	Run 1	Run 2	p	Run 1	Run 2	p		
task 1 time (sec)	132±70	125±111	ns	task 1 time (sec)	151±92	87±39	0.004	task 1 time (sec)	151±92	92±42	0.03
proportion of window cut (%)	25.1±17.2	17.8±15.4	ns	proportion of window cut (%)	20.1±15.6	22.1±16.4	ns	proportion of window cut (%)	20.1±15.6	23.9±17.7	ns
cutting efficiency (pixel ² /sec)	401±182	369±285	ns	cutting efficiency (pixel ² /sec)	303±191	498±239	0.02	cutting efficiency (pixel ² /sec)	303±191	512±259	0.02
cut errors – total	5	1		cut errors – total	1	0		cut errors – total	1	0	
cut error rate (%)	26.7	7.7	ns	cut error rate (%)	5.6	0	ns	cut error rate (%)	5.6	0	ns
task 2 time (sec)	45±24	48±22	ns	task 2 time (sec)	53±20	45±25	ns	task 2 time (sec)	53±20	46±26	ns
maximum errors in one subject	14	7		maximum errors in one subject	5	2		maximum errors in one subject	5	2	
error rate	61.5	54.5	ns	error rate	66.7	62.5	ns	error rate	66.7	66.7	ns

Table 6 Learning curve – pair wise inter-run, within-subject comparison.

2D-3D Subjects	3D-2D Subjects						
	Run 1–2D	Run 2–3D	p	Run 1–3D	Run 2–2D	p	
task 1 time (sec)	132±70	92±42	0.001	task 1 time (sec)	164±104	125±111	0.03
proportion of window cut (%)	25.1±17.2	23.9±17.7	ns	proportion of window cut (%)	20.6±17.5	17.8±15.4	ns
cutting efficiency (pixel ² /sec)	401±182	512±259	ns	cutting efficiency (pixel ² /sec)	281±188	369±285	ns
cut errors – total	5	0		cut errors – total	1	1	
cut error rate (%)	26.7	0	ns	cut error rate (%)	7.7	7.7	ns
task 2 time (sec)	45±24	46±26	ns	task 2 time (sec)	53±21	48±22	ns
maximum errors in one subject	14	2		maximum errors in one subject	5	7	
error rate	61.5	66.7	ns	error rate	66.7	54.5	ns

points yielded no direct differences in outcomes between 2D and 3D visualization, there were no endpoints for which 2D visualization was significantly superior, and some objective endpoints that favor 3D. Once each subject had the opportunity to learn the task from run 1, cutting efficiency in run 2 was significantly improved using 3D compared with 2D visualization. The endoscope was purposely placed at an angle to the plate (Fig. 2A) to necessitate an understanding of depth relationships. Typically, most subjects had to rotate the rongeurs and make multiple passes with the rongeur in and out of the visualization frame. While it is difficult to extrapolate the magnitude of this difference upon a real operative case, even with a task lasting only a few minutes we were able to demonstrate some differences between 2D and 3D visualization.

In designing a repeated task paradigm, we attempted to assess the factor of learning in relation to visualization. Whether subjects used 2D first or second, the results of their attempts remained the same, while those that used 3D second showed significant improvement in speed and efficiency over those who used 3D first (Table 5). In addition, those that performed 2D followed by 3D showed profound improvements in speed on the second run (Table 6). From these results, we conclude that, once familiar with the task, the limitations, and the outcome parameters (via a first run), the subjects were more facile in performing the task using 3D visualization. By extrapolation, once a subject knows the anatomy of the problem, 3D visualization continues to aid in performance. This result was somewhat unexpected; we hypothesized that 3D visualization would be more important in learning the “anatomy” of a task. In light of these results, however, it is clear that 3D endoscopy may have an important role in operative performance, even in situations where the task and surgical anatomy are familiar.

While our findings demonstrate a clear role for 3D endoscopy, the study is not without limitations. In limiting the study population to surgeons recruited from a neuroendoscopy course or a neurosurgery meeting, our subject groups were relatively small. As a result, it is possible that the statistical analyses may be confounded by beta-error; analysis may have shown no significant difference when one actually exists. To that end, it is important not to interpret the negative results as rigidly demonstrative of equivalence between 2D and 3D visualization. However, the small sample population does not negate the positive results found in speed and efficiency. While further subject recruitment might permit more definitive analysis, the qualitative and quantitative results obtained support a role for 3D visualization in neuroendoscopy. We limited the study population specifically to those that had a clear interest or experience in neuroendoscopy. By targeting this population of surgeons, the results would be more clinically relevant to understanding the role of 3D visualization among those with an aptitude for neuroendoscopy. This is in contrast to some other non-neurosurgical studies of 3D visualization in endoscopic/laparoscopic surgery. For example, Votanopoulos et al. studied 2D versus 3D laparoscopy among 36 general surgery residents and medical students. While they found significant benefits to 3D visualization among inexperienced users, those with experience demonstrated no benefit [24]. However, not all of the participants had an interest or aptitude in laparoscopy. Thus, while our subject number was similar to this study, our population was more representative of those that would benefit from advances in neuroendoscopy. Another limitation of the study was the brevity and simplicity of the tasks; a more detailed and lengthy trial would highlight important differences between 2D and 3D visualization, and might more accurately resemble complex transsphenoidal cases. However, the need to provide throughput, as well as a straightfor-

wardly analyzed set of endpoints, necessitated a relatively concise study paradigm. Despite its brevity, the paradigm was able to demonstrate some objective differences between 2D and 3D visualization. Finally, we did not have a strict 2D-2D control group. While this would be ideal, we weighed this against the need to obtain subjective data regarding 3D endoscopic visualization. We wanted each subject to have some exposure to the 3D system. Thus, the alternating visualization paradigm (2D-3D versus 3D-2D) was a compromise to this end.

The advancement of endoscopic transnasal skull base surgery requires high-resolution, precise, real-time visualization. Three-dimensional endoscopy represents an important potential development to aid visualization. When assessed directly against standard 2D endoscopic visualization, 3D was the preferred method for surgeons, both practicing and in-training. Quantitatively, use of 3D endoscopy resulted in increasing efficiency in some repeated tasks. We have utilized this system in operative cases for endoscopic transsphenoidal surgery and sinus surgery, and found the visualization technology to be readily transferable and not cumbersome [25]. Further application of this technology to pre-clinical testing and clinical procedures may provide additional evidence to demonstrate its utility.

Financial disclosure: None of the authors have a financial interest in any specific technique, instrument, or device involved in this case. Visionsense loaned the equipment to the authors to conduct the study, but none of the authors were compensated financially for any involvement in the project.

References

- 1 *Badani KK, Bhandari A, Tewari A et al.* Comparison of two-dimensional and three-dimensional suturing: is there a difference in a robotic surgery setting? *J Endourol* 2005; 19: 1212–1215
- 2 *Taffinder N, Smith SG, Huber J et al.* The effect of a second-generation 3D endoscope on the laparoscopic precision of novices and experienced surgeons. *Surg Endosc* 1999; 13: 1087–1092
- 3 *Chen JC, Levy ML, Corber Z et al.* Concurrent three dimensional neuroendoscopy: initial descriptions of application to clinical practice. *Neurosurg Focus* 1999; 6: e12
- 4 *Perez-Cruet MJ, Fessler RG, Perin NI.* Review: complications of minimally invasive spinal surgery. *Neurosurgery* 2002; 51: S26–36
- 5 *Tirakotai W, Bozinov O, Sure U et al.* The evolution of stereotactic guidance in neuroendoscopy. *Childs Nerv Syst* 2004; 20: 790–795
- 6 *Blavier A, Gaudissart Q, Cadiere GB et al.* Comparison of learning curves and skill transfer between classical and robotic laparoscopy according to the viewing conditions: implications for training. *Am J Surg* 2007; 194: 115–121
- 7 *Chan AC, Chung SC, Yim AP et al.* Comparison of two-dimensional vs. three-dimensional camera systems in laparoscopic surgery. *Surg Endosc* 1997; 11: 438–440
- 8 *Couldwell WT, Weiss MH, Rabb C et al.* Variations on the standard transsphenoidal approach to the sellar region, with emphasis on the extended approaches and parasellar approaches: surgical experience in 105 cases. *Neurosurgery* 2004; 55: 539–547
- 9 *Anand VK, Schwartz TH.* *Practical Endoscopic Skull Base Surgery.* San Diego: Plural Publishing; 2007
- 10 *Cavallo LM, Messina A, Cappabianca P et al.* Endoscopic endonasal surgery of the midline skull base: anatomical study and clinical considerations. *Neurosurg Focus* 2005; 19: E2
- 11 *Kassam A, Gardner P, Snyderman C et al.* Expanded endonasal approach: fully endoscopic, completely transnasal approach to the middle third of the clivus, petrous bone, middle cranial fossa, and infratemporal fossa. *Neurosurg Focus* 2005; 19: E6
- 12 *Kassam A, Snyderman CH, Mintz A et al.* Expanded endonasal approach: the rostrocaudal axis. Part 1. Crista galli to the sella turcica. *Neurosurg Focus* 2005; 19: E3
- 13 *Kassam A, Snyderman CH, Mintz A et al.* Expanded endonasal approach: the rostrocaudal axis. Part II. Posterior clinoids to the foramen magnum. *Neurosurg Focus* 2005; 19: E4
- 14 *Jho HD, Ha HG.* Endoscopic endonasal skull base surgery: part 1 – the midline anterior fossa skull base. *Minim Invas Neurosurg* 2004; 47: 1–8
- 15 *Jho HD, Ha HG.* Endoscopic endonasal skull base surgery: part 2 – the cavernous sinus. *Minim Invas Neurosurg* 2004; 47: 9–15
- 16 *Jho HD, Ma H-G.* Endoscopic endonasal skull base surgery: part 3 – the clivus and posterior fossa. *Minim Invas Neurosurg* 2005; 47: 16–23
- 17 *Laufer I, Anand VK, Schwartz TH.* Endonasal endoscopic extended transsphenoidal, transplanum approach for suprasellar lesions. *J Neurosurg* 2007; 106: 400–406
- 18 *Laufer I, Greenfield JP, Anand VK et al.* Endonasal endoscopic resection of the odontoid in a non-achondroplastic dwarf with juvenile rheumatoid arthritis. Feasibility of the approach and utility of intraoperative iso-C 3D navigation. *J Neurosurg* [in press]
- 19 *Frank G, Pasquini E, Doglietto F et al.* The endoscopic extended transsphenoidal approach for craniopharyngiomas. *Neurosurgery* 2006; 59: ONS75–ONS83
- 20 *Schwartz TH, Fraser JF, Brown S et al.* Endoscopic skull base surgery. Classification of operative approaches. *Neurosurgery* [in press]
- 21 *Wong GK, Zhu CX, Ahuja AT et al.* Craniotomy and clipping of intracranial aneurysm in a stereoscopic virtual reality environment. *Neurosurgery* 2007; 61: 564–568; discussion 568–569
- 22 *Anil SM, Kato Y, Hayakawa M et al.* Virtual 3-dimensional preoperative planning with the dextroscope for excision of a 4th ventricular ependymoma. *Minim Invasive Neurosurg* 2007; 50: 65–70
- 23 *Levy ML, Chen JC, Moffitt K et al.* Stereoscopic head-mounted display incorporated into microsurgical procedures: technical note. *Neurosurgery* 1998; 43: 392–395; discussion 395–396
- 24 *Votanopoulos K, Brunicardi FC, Thornby J et al.* Impact of three-dimensional vision in laparoscopic training. *World J Surg* 2008; 32: 110–118
- 25 *Brown S TA, Singh A, Schwartz TH et al.* Three-dimensional endoscopic sinus surgery: feasibility and technical aspects. *Otolaryngology and Head and Neck Surgery* 2008 [in press]