Robot-assisted endoscopic third ventriculostomy: institutional experience in 9 patients

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OBJECTIVE The endoscopic third ventriculostomy (ETV) is an established and effective treatment for obstructive hydrocephalus. In its most common application, surgeons plan their entry point and the endoscope trajectory for the procedure based on anatomical landmarks, then control the endoscope freehand. Recent studies report an incidence of neural injuries as high as 16.6% of all ETVs performed in North America. The authors have introduced the ROSA system to their ETV procedure to stereotactically optimize endoscope trajectories, to reduce risk of traction on neural structures by the endoscope, and to provide a stable mechanical holder of the endoscope. Here, they present their series in which the ROSA system was used for ETVs.

METHODS At the authors' institution, they performed ETVs with the ROSA system in 9 consecutive patients within an 8-month period. Patients had to have a favorable expected response to ETV (ETV Success Score ≥ 70) with no additional endoscopic procedures (e.g., choroid plexus cauterization, septum pellucidum fenestration). The modality of image registration (CT, MRI, surface mapping, or bone fiducials) was dependent on the case.

RESULTS Nine pediatric patients with an age range of 1.5 to 16 years, 4 girls and 5 boys, with ETV Success Scores ranging from 70 to 90, underwent successful ETV surgery with the ROSA system within an 8-month period. Their intracranial pathologies included tectal tumors ($n = 3$), communicating hydrocephalus from hemorrhage or meningeal disease ($n = 2$), congenital aqueductal stenosis ($n = 1$), compressive porencephalic cyst ($n = 1$), Chiari I malformation ($n = 1$), and pineal region mass ($n = 1$). Robotic assistance was limited to the ventricular access in the first 2 procedures, but was used for the entirety of the procedure for the following 7 cases. Four of these cases were combined with another procedural objective (3 stereotactic tectal mass biopsies, 1 Chiari decompression). A learning curve was observed with each subsequent surgery as registration and surgical times became shorter and more efficient. All patients had complete resolution of their preprocedural symptoms. There were no complications.

CONCLUSIONS The ROSA system provides a stable, precise, and minimally invasive approach to ETVs.

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KEY WORDS hydrocephalus; endoscopic third ventriculostomy; robotic surgical assist; minimally invasive surgery; surgical technique

THE endoscopic third ventriculostomy (ETV) was first performed by Mixter in 1923; he used urological instruments as the means for visualization and perforation of the third ventricular floor. Since then, this procedure has been refined to include choroid plexus coagulation, stereotaxy, and flexible endoscopes.⁶ This has been an attractive procedure when contrasted to CSF shunting, which requires implantable hardware. The fail-

ure and infection rates of indwelling shunts have been an issue to the patients, their families, and surgeons alike.

The probability of success with an ETV procedure can be assessed by factoring in the patient's age, history of a ventricular shunt, and the etiology behind their hydrocephalus. These factors are weighed and measured on a scale known as the ETV Success Score (ETVSS).^{1,2,7} Complications from ETVs usually arise from injuries to nearby

ABBREVIATIONS BA = basilar artery; ED = emergency department; ETV, ETVSS = endoscopic third ventriculostomy, ETV Success Score; EVD = external ventricular drain; OR = operating room.

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structures that are sustained in the process of accessing or perforating the third ventricular floor.^{11,12} In a recent data analysis from the Hydrocephalus Clinical Research Network, forniceal injuries were the most common complication, occurring in 16.6% of cases. This was followed by hyponatremia (3.9%), thalamic contusion (1.8%), and hypothalamic contusion (1.5%). New neurological deficits occurred in 1.5% of cases; one-third of those became permanent.⁸ Other reported complications include pituitary dysfunction, third cranial nerve palsies, or injuries to vascular structures like the basilar artery (BA).^{11,12} Strategies to reduce these injuries demand the ability to reduce manipulation and surgical gestures once the instruments are within the cranium.^{3,11,12} This would prevent unnecessary and, at times, harmful movements and also permit an unencumbered, successful ventriculocisternostomy.

The robotic stereotactic assistance device (ROSA, MedTech) has been applied in minimally invasive neurosurgical techniques since 2007. The ROSA device has aided neurosurgeons with a multitude of minimally invasive procedures, which include lead placement for deep brain stimulators, brain biopsies,⁹ depth electrode placement for seizure monitoring,⁴ laser ablation of epileptogenic foci,^{5,13} and spinal pedicle screw fixation.¹⁰ This robotic surgical assistant empowers the neurosurgeon to perform precise, stereotactic gestures with the aid of stereotaxy and surgical instrument stabilization. Here, we present the first case series and the operative technique in which the ROSA device is used for performing ETV.

Methods

Each patient underwent a standard preoperative workup for hydrocephalus. Imaging studies and clinical history were reviewed to determine the best approach to surgical care. The decision to perform CSF diversion was based on the clinical judgment that symptomatic hydrocephalus was present. An ETV procedure was chosen over a shunting procedure when the ETVSS predicted a high rate of success (≥ 70). The ROSA stereotaxy system was used to optimize the trajectory through the lateral ventricle and foramen of Monro to the floor of the third ventricle.

Preoperative imaging was uploaded into the ROSA work station for trajectory planning. Choice of imaging was determined by clinical judgment. Our preference was to use the imaging acquired during workup if thin-cut sequences were available (CT angiograms or T1-weighted MRI of brain obtained with contrast). If no stereotactic quality imaging was available, we would obtain a new MRI or thin-cut CT sequence.

Our trajectory planning was done using the uploaded images on the ROSA software. We set the target on the floor of the third ventricle just anterior to the BA in the sagittal view. We set a temporary entry point within the foramen of Monro on the right side on coronal and sagittal views. This trajectory was then traced back to the level of the skull, where the entry point was adjusted to a second interim position. The course of the trajectory was analyzed and minor adjustments made to avoid any vascular structures along its course. It was important that the final entry site was positioned at the middle point of the skull

FIG. 1. Configuration of the ROSA system and its setup in relation to the rigid head fixation. Laser registration of facial features is demonstrated. Figure is available in color online only.

thickness, because this will later act as the isometric point during the surgery for any required minor manipulations of the endoscope trajectory. Any additional trajectories were then planned as needed if a secondary procedure was being performed (e.g., needle biopsy).

Once general anesthesia had been induced, the patient was positioned on the operating room (OR) table with the head secured in a Mayfield headholder. If no secondary procedure was being performed, then the patient was placed supine and the ROSA's laser attachment was used for registration based on facial anatomical markers (Fig. 1).

In cases in which there were multiple procedures to be performed, we strategically decided to complete the one that required the most accurate stereotaxy first. Therefore, the procedures that required the biopsies were performed before the ETV to prevent potential reconfiguration in the ventricular system anatomy that could occur with the ETV and ventricular decompression. Each patient was sterilely prepared and draped in the usual fashion. No head shaving or hair cutting was performed.

The ROSA arm directed us to our entry site on the scalp, where we used a No. 15 blade to make a single stab incision through the skin, through which we passed a 3.2-mm-diameter drill bit to make a bur hole through the skull along the trajectory (Fig. 2).

A No. 67 Beaver blade was small enough to pass through the bur hole and was used to make a cruciate incision through the dura mater. At this point we replaced the ROSA device's 3.2-mm-diameter steel bushing with the shorter length 3.2-mm plastic bushing. We then passed a ventricular catheter through the plastic bushing and bur hole into the lateral ventricle. The ventricular catheter was quickly removed and we inserted the endoscope through the bushing, guiding it down the premade tract into the lateral ventricle, where the intraventricular anatomy could be visually identified. For the purposes of endoscopy, we used the Aesculap Paediscop featuring a 3-mm outer diameter scope, with 2 working channels and a 150-mm shaft (Fig. 3). Saline irrigation was administered as needed through

FIG. 2. An electric drill is used to drill a craniotomy at the preplanned area. The ROSA system's instrument port guides the surgeon to this area. A bushing is used within this instrument port, with the appropriate size for the diameter of the drill bit. Figure is available in color online only.

FIG. 3. The drill bushing is swapped out for the endoscope bushing within the ROSA system's instrument port. The Paediscop is then advanced through the bushing into the surgical site of interest. Figure is available in color online only.

one working channel while irrigation egression occurred through the other. Irrigation was used judiciously when the instrument working channel was in use, and liberally when the working channel was open and available for passive CSF egress.

The foramen of Monro was identified in perfect alignment and the endoscope was advanced into the third ventricle. In all instances, the floor of the third ventricle was translucent and we were able to identify the anatomical structures of the mammillary bodies beneath. We chose to perform our ventriculostomy just anterior to the mammillary bodies and BA. We would usually need to adjust the trajectory of the endoscope approximately 1–2 mm to optimize the alignment of our instruments for the fenestration. The ROSA arm was put in the “isometric” movement mode, which restrained the movement of the endoscope at the predefined fulcrum point at the entry point within the skull. The ROSA arm was placed in “slow” movement mode, which allowed for small and precise manipulations of the endoscope by the surgeon. Once the exact trajectory was achieved the arm was locked into position.

A 1.0-mm-diameter Bugbee wire was passed through the working channel of the endoscope to puncture the floor of the third ventricle without electrocautery. Following this step we inserted an Fr-2 Fogarty balloon through the tiny opening and inflated the balloon to dilate the fenestration (Fig. 4).

Once we were satisfied with the fenestration window we would advance the endoscope through the opening to visualize the BA and ensure that the membrane of Liliquist had been opened sufficiently with the fenestration. The endoscope was then gently backed out of the ventricular system while giving special attention to the structures surrounding the foramen of Monro to identify any signs of stretching or bruising. Once the endoscope was removed from the patient's head, the ROSA system's port was then backed away from the patient, and the skin incision was closed with a single 3-0 absorbable monofilament suture.

Results

Between December 2015 and July 2016 we performed 9 ETVs with the aid of the ROSA device. Patient characteristics and outcomes are displayed in Table 1. The ETVSSs ranged from 70 to 90. There were no intraoperative complications, no bruising or inadvertent stretching of neural structures by the endoscope, and no clinical deficits seen in the immediate postoperative period. Bruising or injury to the foramen of Monro and surrounding thalamus was assessed by direct visualization of the structures with the endoscope on completion of the procedure, as well as on postoperative CT scans for all patients. There was no evidence of hemorrhage or edema of the surrounding neural structures associated with the ventriculocisternostomy or its access. We also looked for signs of memory deficits,

FIG. 4. An Fr-2 Fogarty balloon is advanced through the Paediscop's instrument port, which dilates the third ventricular floor to create and maintain the fenestration. Figure is available in color online only.

TABLE 1. Characteristics and outcomes in 9 patients with hydrocephalus

Case No.	Age (yrs)	Sex	Diagnosis	Additional Procedure	Preop Imaging	ETVSS	Completed w/ ROSA	30-Day Outcome	Prior Shunt	Total Op Time (mins)
1	11	M	Tectal mass	Tectal biopsy	MRI	90	No	Success	No	150
2	3	F	Tectal mass, shunt failure	Tectal biopsy + shunt removal	MRI	70	No	Success	Yes	128
3	2	M	Porencephalic cyst (history of neonatal ICH)	None	CT	70	Yes	Success	No	143
4	14	M	Chiari I malformation	Suboccipital craniectomy	Intraop CTA	90	Yes	Success	No	158
5	11	M	Tectal mass	None	MRI	90	Yes	Success	No	91
6	16	F	Aqueductal stenosis	None	MRI	90	Yes	Success	No	85
7	1.5	M	Posthemorrhagic hydrocephalus	None	MRI	70	Yes	Success	No	101
8	12	F	Leptomeningeal metastasis	None	MRI	70	Yes	Death	No	64
9	12	F	Pineal region tumor	Tectal biopsy	CT, MRI	90	Yes	Success	No	65

CTA = CT angiography; ICH = intracranial hemorrhage.

limb or face weakness, or decrease in cognition. At the 30-day follow-up, no patient in our cohort required a shunt or a repeat ETV. There was 1 death in our cohort, which was related to progression of the patient's primary disease and not to the procedure.

The time required to perform the operation decreased over this series of 9 patients, which is reflective of the learning curve for using the ROSA system. Whereas the early procedures took more than 2 hours to complete, this time decreased to just over 1 hour for the most recent operations (Fig. 5). This objectively demonstrates our learning curve with the familiarity of the software, registration, and gestures with the ROSA system. With increasing experience, the roughly 1-hour operating time (from head pinning to final suture) for performing the robot-assisted ETV is comparable to the expected operating times for performing an ETV using the freehand technique.

It is important to note that our first 2 attempts at a ROSA-aided ETV were not completed in their entirety using the robotic assistance arm. In those 2 cases the ROSA system was used for stereotaxy and for drilling the bur hole. However, our 3.2-mm steel bushing was too long to allow our endoscope to reach the third ventricle. Per

our request, the MedTech company constructed a shorter 3.2-mm peak bushing, which permitted the robotic arm to work closer to the skull and allowed the 150-mm-long endoscope to reach into the third ventricle. This new bushing was used for the subsequent 7 cases and enabled us to take full advantage of the robotic arm from start to finish of each case.

Illustrative Cases

Case 6

History and Examination

This illustrative case was the sixth patient in our series of ROSA-aided ETVs. She was a 16-year-old girl who had presented with an acute-on-chronic worsening of her frontal headaches, which were now associated with nausea and vomiting. She presented to the emergency department (ED) for further evaluation, at which time an MR image was obtained; it revealed triventriculomegaly secondary to aqueductal stenosis (Fig. 6).

On examination she was awake and alert, although notably in distress from her headaches and nausea. She was admitted from the ED and planned to undergo a ROSA-aided ETV the next day. Her ETVSS was 90.

Operation

In the operating room, the patient was placed supine with the head in slight flexion. She was placed in the Mayfield headholder, which was attached to the OR table, and then to the ROSA system. Her MRI sequence was uploaded with the preplanned trajectory for the ETV (Fig. 7).

The registration and ventricular access were performed uneventfully as described earlier. Of special note, the entire reach of the endoscope was maximized against the ROSA instrument's port bushing. This prevented us from advancing the scope through the fenestrated floor to look at the basilar cistern. Although it was not a problem with this case, it might present as a future problem if more travel was desired with the scope. The patient was awakened from anesthesia and brought to the recovery room in good condition.

FIG. 5. Graph showing operating time in minutes over the course of treating our 9 patients in this series. Familiarity and experience with the ROSA system was probably a contributing factor in improving operative efficiency. Figure is available in color online only.

FIG. 6. Case 6. A patient with congenital aqueductal stenosis. The MRI studies show stenosis at the cerebral aqueduct (left), and mild ventriculomegaly (right).

Postoperative Course

Postoperatively, she reported a resolution of her nausea and an overall improvement in her headaches and was discharged home on postoperative Day 2. She was seen in clinic 2 weeks later with a new MRI study, which demon-

strated resolution of her ventriculomegaly. More importantly, she reported a marked reduction in her headache intensity and frequency. She did not develop any new neurological deficits.

Case 9

History and Examination

The ninth patient to have undergone a ROSA-aided ETV was a 12-year-old girl who was seen in the ED for week-long symptoms of headaches, nausea, and vomiting. Her symptoms acutely worsened on the morning prior to admission, when she became listless and obtunded. Her examination results were notable in that she was minimally arousable and had upgaze palsies bilaterally. A head CT was obtained, which showed triventriculomegaly with a hyperdense region in the pineal region. An external ventricular drain (EVD) was placed at bedside. Subsequent MRI was revealing for a heterogeneously enhancing pineal region mass causing aqueductal stenosis (Fig. 8).

The MRI also included sequences for neuronavigation.

FIG. 7. Case 6. The ROSA software trajectory planning of surgical intervention from preoperative imaging. The trajectory is aiming toward the third ventricular floor. Figure is available in color online only.

FIG. 8. Case 9. A patient with aqueductal stenosis secondary to an expansile tectal mass. The MRI studies show mild ventriculomegaly with an EVD in place (A), aqueductal stenosis secondary to an expansile tectal mass (B), and the mass effect related to the lesion (C).

The patient's alertness improved significantly following aggressive CSF drainage. After careful evaluation, it was decided that she would require a pineal region tumor biopsy and an ETV. Her predicted ETVSS was 90.

Prior to the planned procedure, we used the ROSA software to plan trajectories for the 2 procedures. First, we planned the pineal tumor biopsy (Fig. 9). Second, we planned the ventriculocisternostomy (Fig. 10).

Operation

Once the planning was deemed adequate and suitable for a surgery, we brought the patient to the operating room and she was placed under general anesthesia. The Mayfield was strategically placed such that its right frontal area where the ETV was to be performed was not in the way, nor in the way of the area of the biopsy. The ROSA robot was then attached to the Mayfield headholder, and we began the registration sequence. We then obtained facial registration through the ROSA's laser acquisition. Once the anatomy was satisfactorily registered, we programmed the ROSA to move to both sites on the scalp to ensure feasibility of both robotic and surgical access. We then prepared and sterilized both the planned ETV site and the biopsy site.

The biopsy of the pineal region mass was performed first, because we did not want to create incongruencies between the image registration and the actual anatomical configuration that could result if we did the ETV first. Using the ROSA system software, we selected the entry point for the biopsy procedure first. The robotic arm traveled to the area of the biopsy. Once docked at the preplanned area, we created a single stab incision. A hand drill was used to make the craniotomy and a No. 67 Beaver blade was used to make the durotomy. Once the durotomy was made, we swapped out the drill bushing to a 1.8-mm polyetheretherketone bushing. The VarioGuide biopsy needle was then passed through this new bushing. The travel distance of the biopsy needle was calculated from the ROSA software. Once at the travel distance, tissue in all 4 quadrants was obtained and confirmed to be tumor tissue, based on frozen-section diagnosis. The VarioGuide biopsy needle was removed, and the stab incision was closed with a single 3-0 monofilament absorbable suture.

Next, our attention was turned toward the ETV procedure.

Through the ROSA interface, we executed the command for the robotic arm to travel to the next preplanned trajectory, which was for the ETV. The ETV was performed as described in the *Methods* section, using a single stab incision at the area marked by the ROSA system. Following the uneventful ETV, her EVD was left in place, and kept at the higher level of 25 mm Hg to permit CSF flow and patency through the new ventriculocisternostomy.

Postoperative Course

The patient was kept intubated and sedated in her immediate postoperative period, but once extubated several days later, her headaches and lethargy completely resolved. She continued to have upgaze palsies and diplopia related to the mass effect from her tumor. She was eventually weaned off her EVD after 4 days postoperatively. She was discharged to an inpatient rehabilitation ward on postoperative Day 9. Her tumor pathology findings were for a pineoblastoma, and she has been undergoing rounds of chemotherapy and proton beam therapy.

Discussion

Our series of 9 patients demonstrated improvement of preoperative symptoms in the immediate postoperative period. No patients had any adverse outcomes related to the procedures. These patients were followed up in clinic within a few weeks postoperatively and at regular intervals up to 6 months. All patients reported durable symptomatic improvement or resolution of their preoperative symptoms. One patient died as a result of her primary disease process. None required a CSF shunt. Through our first 9 cases of the ROSA-aided ETV, we have demonstrated that a learning curve exists; but once we were familiar with the system, the surgical time for the ROSA-aided ETV approached the same amount of time as that needed to perform a freehand ETV. Moreover, incision sizes were smaller, and minimal manipulation by the endoscope was achieved.

The ROSA-aided ETV has several potential advantages over the conventional, freehand ETV. First, the robot system adds stereotaxy to allow for precise navigation to the area of surgical attention. By virtue of this, it allows for a smaller bur hole and smaller incision, because there is less

FIG. 9. Case 9, first procedure. The ROSA software trajectory planning of surgical intervention from preoperative imaging. The trajectory is aiming toward the tectal mass. Figure is available in color online only.

need for manipulation and adaptation of the endoscope angle and travel. With the additional advantage of a stabilizing arm, this can become a single-surgeon operation in which the surgeon can use both hands to perform the procedure and not be burdened by the need to stabilize or hold the endoscope. The reduced mobility of the scope as guided by the robotic arm has the potential to improve safety of the procedure by protecting the fornices and thalamus from inadvertent excessive surgical maneuvering,⁸ but it might limit the surgeon's flexibility in the case of a complication. However, in the event of unexpected bleeding significantly outside of the trajectory path, the robotic arm can be immediately and rapidly mobilized out of the operative field for the surgeon to return to a freehand technique, with its accompanying maneuverability of the endoscope. This requires only 1 or 2 seconds, but would necessitate a brief removal of the endoscope from the brain and then replacement.

Another advantage of the robotic assist is that it allows the surgeon to position the patient in any direction that is indicated for multiple procedural objectives. The per-

ceived trajectory or angle of the endoscope can be onerous to determine in a head position other than neutral. This advantage was demonstrated when our patient was positioned in the three-quarter lateral position for a suboccipital decompression. With the head turned in the three-quarter lateral position, landmarks used in the freehand performance of an ETV can be difficult and disorienting. With the ROSA system we were able to position the patient for other planned procedures, and then perform the ETV with the patient already positioned for such procedures. This saves time because it also obviates the need for repositioning and redraping, which would otherwise be needed if the patient was to be placed in varying positions for multiple procedures in the same setting.

One of the most notable disadvantages of the ROSA-aided ETV is additional time needed for setup. It takes time and familiarity to register, orient, and set up the robot to perform the surgery. This familiarity is necessary for all members of the operative team to master and carries a notable learning curve. As our series progressed, total operating times decreased substantially and eventually

FIG. 10. Case 9, second procedure. The ROSA software trajectory planning of surgical intervention from preoperative imaging. The trajectory is aiming toward the third ventricular floor. Figure is available in color online only.

were no more than 20 or 30 minutes longer than a free-hand ETV procedure and were comparable in duration to similar cases in which a frameless stereotaxy system was used. We also acknowledge the capital costs required to obtain the ROSA robot itself, which may not be justified outside of high-volume centers where this system would be used frequently for this and other indications. The other disadvantage to this system is the ability of the endoscope to reach the ventricular/cistern membrane in patients with larger heads from longstanding hydrocephalus. This problem was realized after our procedure performed on the patient in Case 6. The length of the endoscope that we used was 15.0 cm, and the ROSA device's port with the bushing is 3.7 cm long, therefore only allowing for 11.3 cm of endoscope to be used to reach the ventricular floor. The instruments, however, can be used to reach a farther distance. This problem can be resolved with use of a longer endoscope, or with a lower-profile bushing.

Limitations of this report include its relatively small number of patients and the short follow-up times for determining long-term efficacy of the fenestrations in compari-

son with historical cohorts. There were no complications or incidents of forniceal or thalamic injuries in this series, which demonstrates the feasibility of the procedure. It suggests the potential of robotic assistance to improve the safety of ETVs, but larger comparative studies are needed before that assessment can be made. Future studies are warranted to compare outcomes between traditional and robotically assisted ETVs to determine whether a clinically significant benefit may exist.

Conclusions

The ROSA system provides a stable, precise, and minimally invasive approach to ETVs. Future studies are warranted to determine whether hydrocephalus outcomes might be improved and complications reduced through the adoption of this new technology.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: Hoshide, Calayag, Meltzer, Gonda. Drafting the article: Hoshide, Calayag, Meltzer, Gonda. Critically revising the article: Hoshide, Calayag, Meltzer, Gonda. Reviewed submitted version of manuscript: Hoshide, Calayag, Meltzer, Gonda. Approved the final version of the manuscript on behalf of all authors: Hoshide. Statistical analysis: Hoshide, Calayag, Meltzer, Gonda. Administrative/technical/material support: Hoshide, Calayag, Meltzer, Gonda. Study supervision: Hoshide, Calayag, Meltzer, Gonda.

Supplemental Information

Previous Presentations

Portions of this work were presented in abstract form and as a podium presentation at the Congress of Neurological Surgeons (CNS) Annual Meeting held in San Diego, CA, in October 2016.

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