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Original Article

The Efficacy of VP Shunt Entry Area Recommender (VPSEAR) in Keen's Point VP Shunt using Computer Simulation and 15 3D Skull Models

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Abstract

Objective: The accuracy of the free-hand technique in VP shunt catheter placement is not high due to patients' dissimilarities and different severity of hydrocephalus. Although navigator-assisted VP shunt is more accurate, not every neurosurgical center can afford neuronavigation. Therefore, we developed a software named VP Shunt Entry Area Recommender (VPSEAR), using computer science combined with neurosurgery knowledge to provide each patient's recommended entry and ventricular catheter length. Here, we conducted an evaluation of our program efficacy in simple hydrocephalus patients.

Methods: Fifty hydrocephalus cases were randomly chosen from our medical records. Patient data, including age, sex, cause of hydrocephalus, and hydrocephalus severity, were collected. VP shunt simulation was evaluated by two methods: 1) computer simulation and 2) fifteen 3D skull model simulations to compare the VPSEAR recommended entry point at the parietal region vs. the theoretical Keen's point. Locations of ventricular catheter tips were recorded and categorized into proper and improper locations.

Result: One hundred samples (50 cases, both sides) were evaluated. VPSEAR achieved a proper location of ventricular catheter tip for 86/100 (86%). In Keen's point, three different lengths of ventricular catheter tip were evaluated and showed a proper location in 86/100 (86%), 46/100 (46%), and 6/100 (6%) for ventricular catheter lengths of 6, 7, and 8 cm respectively. In 92% of VPSEAR's group, the majority of catheters were in the ventricle, and in only 8 cases, the majority of catheters were in the brain, while 86% of the majority of catheters in Keen's group were in the ventricle. VPSEAR recommended ventricular catheter length was 64.92 ±10.21 mm. The mean displacement from the VPSEAR entry point to Keen's point was 21.29 ± 16.12 mm. Regarding the 3D skull model simulation, our study showed the angle of deviation from the theoretical perpendicular trajectory was 8.64 ± 3.38 degrees.

Conclusion: Our VPSEAR is a promising, inexpensive option for locating ventricular entry points using computer science and neurosurgery knowledge. VPSEAR showed higher accuracy than Keen's point in both computer simulation and 3D skull model simulation evaluations.

Keywords: VP shunt, program, accuracy, simulation, 3D skull

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บทคัดย่อ

การประยุกต์ใช้โปรแกรมคำนวณจุดแทงสายระบายในโพรงสมองในการจำลองทางคอมพิวเตอร์และกะโหลกเทียม 3 มิติ จำนวน 15 หัว

ศศิกานต์ สุขห่อ, พ.บ., วิชญ์ ยินดีเดช, พ.บ.

หน่วยศัลยกรรมระบบประสาท ภาควิชาศัลยศาสตร์ คณะแพทยศาสตร์ มหาวิทยาลัยธรรมศาสตร์

วัตถุประสงค์: ความแม่นยำของการผ่าตัดวางสาย/ท่อระบายน้ำจากโพรงน้ำในสมองลงมาสู่ช่องท้อง โดยวิธี free hand ยังมีความแม่นยำค่อนข้างต่ำ เนื่องจากตำแหน่งที่ใช้เป็นจุดอ้างอิงและปัจจัยเรื่องขนาดของโพรงสมองมีความแตกต่างในแต่ละบุคคล อีกหนึ่งตัวเลือกที่แพทย์สามารถนำมาใช้วางแผนการผ่าตัดคือการใช้เครื่องช่วยกำหนดและยืนยันจุดหรือระบบนำวิถี (neuronavigator) อย่างไรก็ตามเครื่อง neuronavigation มีราคาที่สูงมาก จึงไม่ได้มีใช้แพร่หลายในทุกโรงพยาบาลที่มีการผ่าตัดทางระบบประสาท ผู้วิจัยจึงมีแนวคิดที่จะนำเทคโนโลยีคอมพิวเตอร์เพื่อใช้ในการผลิตซอฟต์แวร์สร้างโปรแกรมที่นำข้อมูลภาพถ่ายซีทีแสกนมาช่วยคำนวณบริเวณที่สามารถใช้เป็นจุดเข้าแบบอัตโนมัติและคำนวณความยาวของสาย ventricular end โดยประมวลผลและแสดงผลร่วมกับภาพถ่ายกะโหลกที่ซ้อนกับโพรงสมองด้วยโปรแกรม 3 มิติจะช่วยทำให้การผ่าตัดวางสาย/ท่อระบายน้ำจากโพรงน้ำมีความละเอียดแม่นยำมากยิ่งขึ้น ดังนั้นผู้วิจัยจึงต้องการที่จะประยุกต์ใช้โปรแกรมคำนวณจุดแทงสายระบายในโพรงสมองเพื่อทดสอบประสิทธิภาพความแม่นยำของโปรแกรมในผู้ป่วยที่มีโพรงสมองคั่งน้ำที่ไม่ได้มีความซับซ้อน

วิธีการศึกษา: สุ่มเลือกผู้ป่วยที่ได้รับการวินิจฉัยเป็นโรคโพรงสมองคั่งน้ำทั้งหมดจำนวน 50 รายจากเวชระเบียน ทำการเก็บข้อมูลของผู้ป่วยประกอบไปด้วย อายุ เพศ สาเหตุของโรคโพรงสมองคั่งน้ำและปัจจัยเรื่องขนาดของโพรงสมอง จำลองผ่าตัดวางสาย/ท่อระบายน้ำจากโพรงน้ำในสมองลงมาสู่ช่องท้องสองวิธี 1. จำลองแทงเข้ากะโหลก (entry point) เพื่อให้เข้าถึงโพรงสมองในคอมพิวเตอร์ 2.จำลองในโมเดลกะโหลกเทียม 3 มิติ จำนวน 15 หัวโดยใช้จุดที่ได้จากการคำนวณของโปรแกรมเทียบกับการใช้จุดคีน เพื่อดูตำแหน่งปลายสายในโพรงสมอง

ผลการศึกษา: ผู้ป่วยทั้งหมด 50 ราย ทำการจำลองทั้งสองข้างแบ่งเป็นจำลอง 100 ครั้ง พบว่าร้อยละ 86 ปลายสายอยู่ในตำแหน่งที่เหมาะสม เมื่อจำลองโดยการใช้จุด entry point ที่ได้จากการคำนวณของโปรแกรม ในขณะที่จุดของคีนพบว่าอยู่ในตำแหน่งที่เหมาะสม ร้อยละ 86, ร้อยละ 46 และร้อยละ 6 ในความยาวของสาย ventricular end ที่ 6 ซม. 7 ซม.และ 8 ซม.ตามลำดับ ร้อยละ 92 ของกลุ่มที่ใช้จุด entry point ที่ได้จากการคำนวณของโปรแกรมพบว่าปลายสายส่วนใหญ่อยู่ในโพรงสมอง มีเพียง 8 รายที่ปลายสายส่วนใหญ่อยู่ในเนื้อสมอง ในขณะที่จุดของคีนปลายสายส่วนใหญ่อยู่ในโพรงสมองเพียงร้อยละ 86 ความยาวของสาย ventricular catheter ได้จากการคำนวณของโปรแกรมคือ 64.92 ±10.21 มิลลิเมตร ค่าเฉลี่ยของระยะกระจัดของจุด entry point ได้จากการคำนวณของโปรแกรมและจุดของคีนคือ 21.29 ± 16.12 มิลลิเมตร เมื่อทำการจำลองในโมเดลกะโหลกเทียม 3 มิติ พบว่ามุมที่เบี่ยงเบนจากการทำมุมตั้งฉากระหว่างแทงเข้าโพรงสมองคือ 8.64 ± 3.38 องศา

สรุป: โปรแกรมคำนวณจุดแทงสายระบายในโพรงสมองคาดว่าจะเป็นประโยชน์ต่อวงการแพทย์ สามารถช่วยให้การผ่าตัดวางสาย/ท่อระบายน้ำจากโพรงน้ำมีความละเอียดแม่นยำมากยิ่งขึ้นช่วยลดค่ารักษาของสถานพยาบาลและประหยัดค่าใช้จ่ายของผู้ป่วย ซึ่งโปรคำนวณจุดแทงสายระบายในโพรงสมองพบว่ามีความแม่นยำมากกว่าจุดของคีนทั้งการจำลองในคอมพิวเตอร์และการจำลองในโมเดลกะโหลกเทียม 3 มิติ.

คำสำคัญ: ผ่าตัดวางสาย/ท่อระบายน้ำจากโพรงน้ำ, โปรแกรม, ความแม่นยำ, การจำลอง, โมเดลกะโหลกเทียม 3 มิติ

Introduction

Ventriculoperitoneal (VP) shunt is one of the most common procedures in neurosurgery. Two main techniques used to insert a ventricular catheter are the free-hand and navigator-assisted technique. The navigator-assisted technique is the most accurate, but some neurosurgery centers, especially in low-to-moderate-income countries, cannot afford the navigation system.[1,2] The free-hand technique is more common in global neurosurgical practice; however, according to the literature, it is not highly accurate.[3-5] To solve this problem, many groups have proposed their own techniques to enhance the accuracy of the free-hand VP shunt without using navigation.[1-5]

Two challenges regarding free-hand VP shunt surgery are determining the proper entry location and determining the appropriate ventricular catheter length in each case. Several entries such as Kocher's, Keen's, Dandy's and Frazier's points, all marked by an external landmark6and their recommended ventricular catheter lengths have been proposed for many decades and are in use around the world.[6,7] The improper length and entry point would cause shunt failure, especially within the first year, in 39%8. The most common cause of shunt failure is ventricular catheter tip occlusion by tissue debris from ventricular structures including ependymal cells, choroid plexus, and leptomeninges[8]. However, the proper length of the ventricular catheter and entry point are considerable for long-term preservation of VP shunt function9. Therefore, the same exact measurement for each proposed entry is only sometimes accurate for some patients because there are differences in patients' anatomies and various hydrocephalus severities. For example, Keen's point is almost located 2.5-3 cm. superiorly and posteriorly to the ear pinna[10], but each patient has a different ear size and hydrocephalus severity. One previous study showed only 65% accuracy of Keen's point under the free-hand technique.[11] Therefore, Keen's point is most commonly used in our institution and several neurosurgical units6 because there is a short distance to pass through the peritoneal cavity, which requires no additional incision.[10] Initially, we developed our software, VP Shunt Entry Area Recommender (VPSEAR), to improve the accuracy of the ventricular entry procedure using Keen'point.[12] VPSEAR was developed using knowledge of computer science combined with neurosurgery. This program needs no navigation system; it requires only a thin slice of computed tomography (CT) of the brain in a Digital Imaging and Communications in Medicine (DICOM) file as input. Then, it will calculate an individual entry point recommended to access a ventricle from the parietal region. In this study, we evaluated our program efficacy by simulating ventricular punctures in a computer simulation, and we also confirmed them by additionally simulating the ventricular punctures under a surgeon's hand with fifteen 3D skull models under a navigator, which should better represent a real-life situation.

Principle of VPSEAR

After the DICOM file is uploaded in VPSEAR, the 3D models of the surfaces of the skull, lateral ventricles, and the ear pinna are created from point clouds, which were constructed from their Hounsfield units (HU). The model is readjusted into standard

Frankfurt alignment. 3D vectors are created orthogonally at the surface of the skull at the parietal region superiorly and posteriorly to the ear pinna above the temporalis muscle. VPSEAR automatically selects the skull's largest circular area, in which its internal point's vectors project onto the atrium of the lateral ventricle. The program produces the location of the center, the radius, and the ventricular catheter length. The location is defined simply by vertical and horizontal distances from the neurosurgeon's predefined reference point, which is set as the top of the ear pinna. The VPSEAR's graphic user interface (GUI) is user-friendly, and the VPSEAR report is easy to understand (Fig. 1A and 1B).

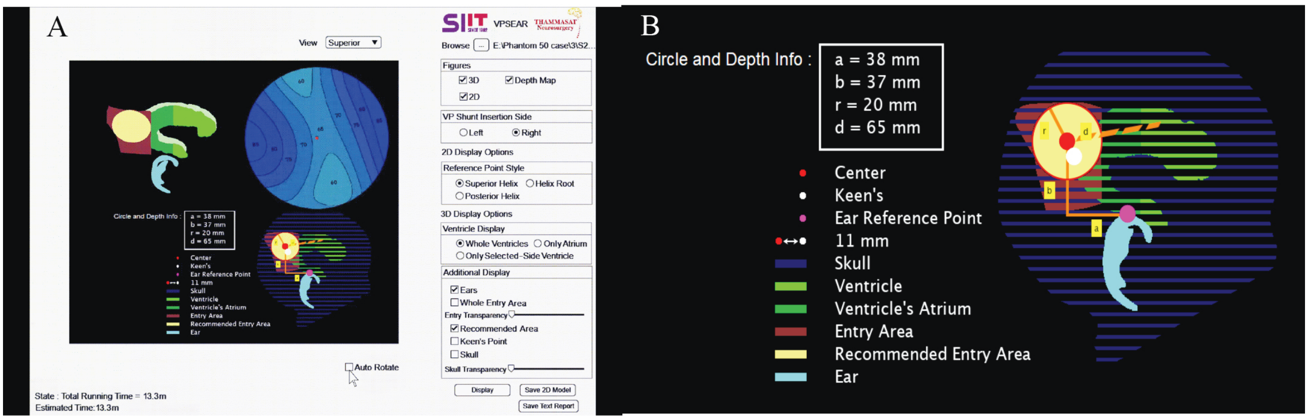

Figure 1 **A** Graphic user interface of VPSEAR. **B:** VPSEAR report in the sample case.

Each patient takes about 5-15 minutes to process and show the result. The duration depends on the computer's performance and the number of slides used in the calculation. VPSEAR was experimentally proven to be very accurate in another study. The accuracy was obtained by verifying the position of the ventricular catheter end tip using the recommended entry point and ventricular catheter length from the VPSEAR with different computer simulations, 3D Slicer® (Massachusetts, USA). Details of the VPSEAR programming algorithm and its verification will not be described here as it is already published in another computer science journal.[8,12]

Method

Our study was approved by the university ethic committee (MTU-EC-SU-6-290/64). We searched and randomly chose 50 hydrocephalus patients treated in our department between July 2020 and June 2021. We excluded patients with abnormal ventricular anatomy to focus on the efficacy of VPSEAR in simple hydrocephalus. We excluded abnormal scalp and skull surface cases to evaluate normal reference points. Cases with abnormal ear shape were also excluded. In addition, we excluded cases with inadequate DICOM file data and cases with prior VP shunt placement. 3D experimental models were printed for 15 cases, and a total of 50 cases were evaluated in computer simulation.

Data regarding age, sex, cause of hydrocephalus, and hydrocephalus severity were collected. Quantitative data was presented with mean ± standard deviation and range. Qualitative data was presented with percentages. VPSEAR was then used to calculate the recommended entry for selected 50 cases on both sides. A total of 100 samples were evaluated. Our study used RadiAnt® DICOM Viewer version 2022.[1] (Medixant, Poland) to assess program accuracy by computer simulation. Interested researchers can easily reproduce our evaluation steps.

Computer Simulation Evaluation Steps

After selecting the DICOM data of a patient, we clicked "3D MPR" for multiplanar reconstruction. We adjusted the image set to the proper Frankfurt plane in all views, including axial, coronal, and sagittal views. The midline was located by falx cerebri identification in axial view. In the coronal view, the superior and inferior orbital rims were adjusted to the symmetric position. Finally, the line connecting the inferior orbital rim and the superior rim of the external auditory canal was used as a reference in the sagittal view. After the Frankfurt plane adjustment, we used the sagittal view to search for the top of the pinna as a reference point. Then, we measured the superior and posterior lengths from this reference point to reach the entry point recommended by VPSEAR. From this point, a perpendicular line was created, and an orthogonal trajectory was confirmed in the Trajectory 1 and 2 views in Radiant®. Finally, the length of the simulated ventricular catheter, also calculated by the program, was created perpendicularly to the inner cortex of the skull surface toward the ventricle. We recorded the position of the tip and categorized it as "proper position" (ipsilateral frontal horn or body of lateral ventricle) or "improper position" (contralateral lateral ventricle, third ventricle, or brain parenchyma). We used classification similar to previous studies.9,10 (9,13) Both sides of the ventricle were simulated and recorded. After evaluation of VPSEAR, these steps were done on both sides using Keen's landmark instead, which was defined as 3 cm superiorly and 3 cm posteriorly to the reference point. We also recorded displacement between VPSEAR entry and theoretical Keen's point. We evaluated ventricular catheter length in 6, 7, and 8 cm in the Keen's point simulation. Figure 2 shows steps in the computer simulation.

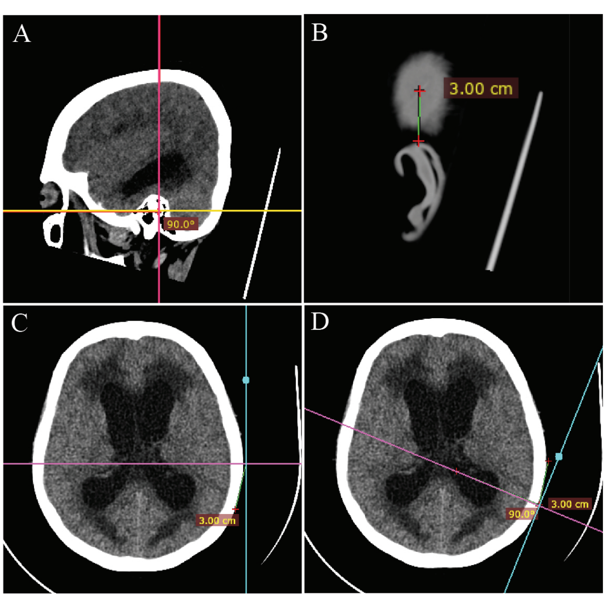

Figure 2 Computer simulation steps A: The proper Frankfurt alignment was shown in sagittal view (Yellow line). B&C: In this example, Keen's landmark was measured from the top point of the ear pinna in 3 cm superiorly and 3 cm posteriorly. D: In the axial view, we used an angle tool to make a perpendicular line from the skull toward the ventricle.

3D Skull Models Simulation Evaluation Steps

To demonstrate a real-life possibility of an angle deviating from the theoretical perpendicular trajectory due to a surgeon's hand, we used 15 cases of 3D skull models to simulate ventricular puncture under a navigator (Brainlab®, Munich, Germany). Our models were printed with Polylactic acid plus (PLA+) by a Fused Deposition Modelling (FDM) 3D printer using DICOM data. (Figure. 3A and 3B) The model simulation began with 3-point head fixation by skull clamp and registered by using bone surface navigator registration in a nearly lateral position, the same as during parietal VP shunt surgery. Entry points of VPSEAR and Keen's were measured and marked. Then, a navigator probe was used to simulate ventricular puncture in each entry. The location of the ventricular catheter tip and average deviation from the perpendicular trajectory were recorded. Two different surgeons were evaluated under senior surgeon supervision, and we used the average of the two results. The same procedures were done for the other side. We also evaluated 6, 7, and 8-cm lengths in Keens' point, the same as in the prior computer simulation. Figure 3C and 3D show the 3D skull model simulation.

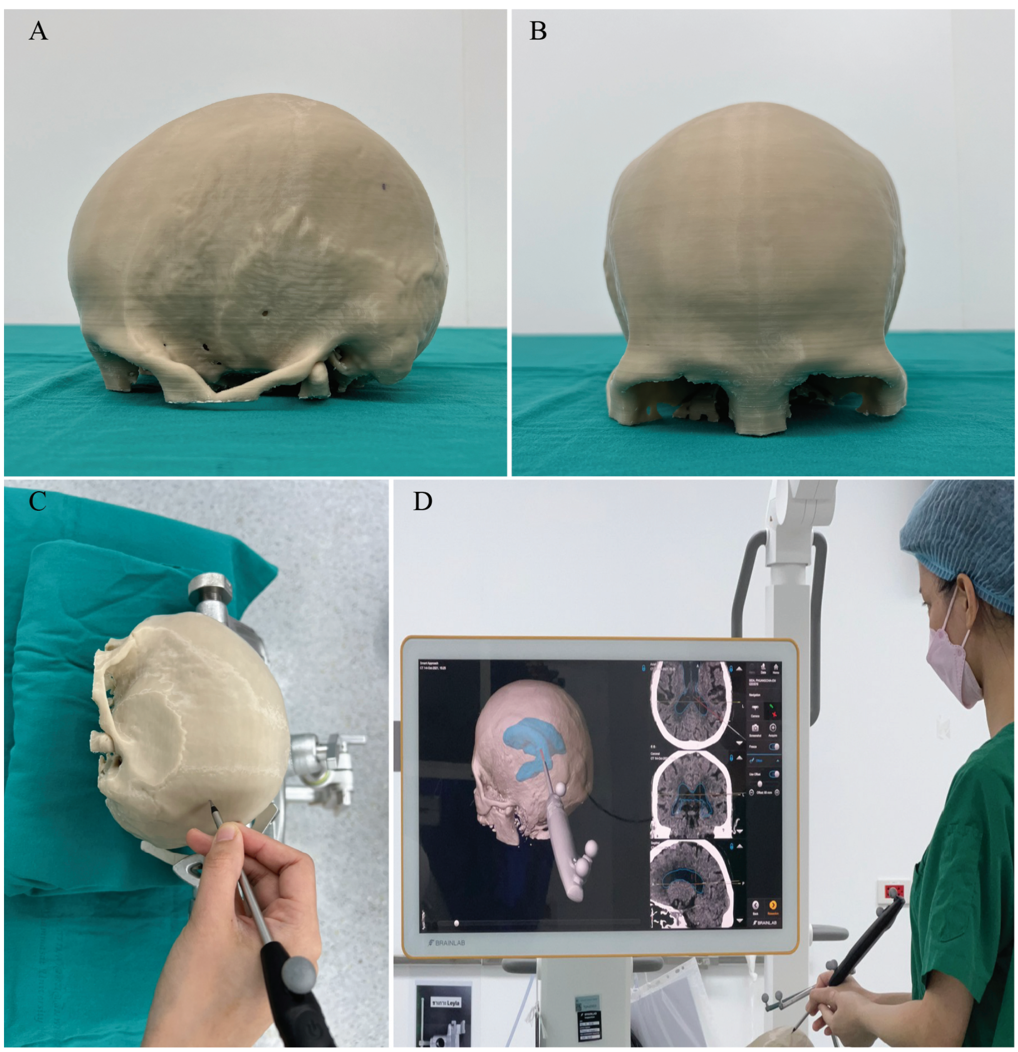

Figure 3 A&B: 3D skull model. C&D: 3D skull model simulation.

Result

Between July 2020 and June 2021, we reviewed CT data in hydrocephalus patients and were excluded for various reasons. (Figure 4) Finally, we randomly chose 50 cases as our sample to simulate in computer and selected 15 cases for 3D skull models to simulate ventricular puncture under a navigator.

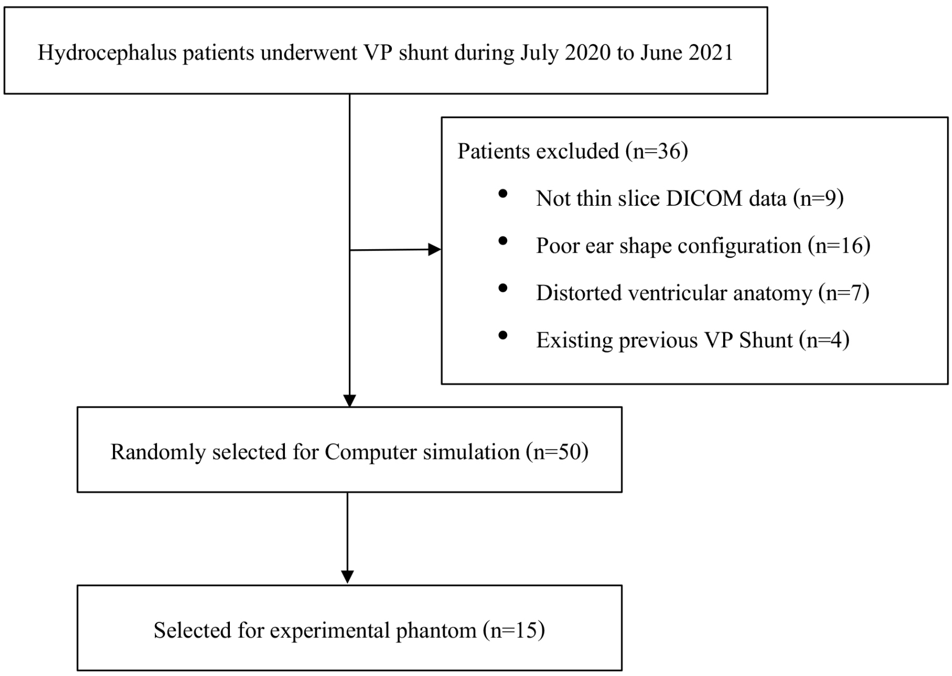

Figure 4 Study flow

Patient characteristic

The mean age of the 50 patients was 61.52 ± 20.47, ranging from 6 to 90. Fourteen (28%) of the patients were male. Causes of hydrocephalus were tumor (32%), aneurysmal subarachnoid hemorrhage (32%), normal pressure hydrocephalus (NPH) (22%), post intracerebral hemorrhage (10%), and CNS infection (2%). Patient characteristic data are presented in Table 1.

Hydrocephalus data

Mean frontal horn ratio was 0.41 ± 0.06, ranging from 0.24 to 0.63. Mean Evan's index was 0.34 ± 0.05, ranging from 0.26 to 0.58. Mean temporal horn width was 9.17 ± 4.69 mm., ranging from 1.08 to 20.70. Mean third ventricle width was 12.29 ± 3.53 mm., ranging from 4.38 to 21.30 mm. Hydrocephalus data are also presented in Table 1.

Table 1 Patient Characteristic

Variable		N = 50
Age (year)		61.52 ± 20.47 (6-90)
Sex	Male	14 (28%)
	Female	36 (72%)
Cause of hydrocephalus	ICH, IVH	5 (10%)
	SAH	16 (32%)
	NPH	11 (22%)
	Tumor	16 (32%)
	Infection	2 (4%)
Hydrocephalus Data (mm.)	Frontal horn ratio	0.41 ± 0.06
	Evan's index	0.34 ± 0.05
	Temporal horn width	9.17 ± 4.69
	Third ventricle width	12.29 ± 3.53

Abbreviation: AVM=arteriovenous malformation, AVF=arteriovenous fistula, ICH=intracerebral hemorrhage, IVH=intraventricular hemorrhage, NPH=normal pressure hydrocephalus, SAH=subarachnoid hemorrhage

VPSEAR Evaluation in Computer Simulation

Fifty cases of CT brain were evaluated on both sides. VPSEAR achieved a proper location of ventricular catheter tip for 86/100 (86%). Fourteen samples showed improper location: in the brain nine samples, contralateral, body three samples, and two samples in the third ventricle. In Keen's point, three different lengths of the catheter were evaluated and showed a proper location in 86/100 (86%) with a 6-cm catheter, 46/100 (46%) with a 7-cm catheter, and 6/100 (6%) with an 8-cm catheter. In 92% of VPSEAR's group, the majority of catheters were in the ventricle; in only 8 cases, the majority of catheters were in the brain, while 86% of the majority of catheters in Keen's group were in the ventricle. Mean VPSEAR recommended ventricular catheter length was 64.92 ±10.21 mm, ranging from 37 to 99 mm. Mean displacement between the VPSEAR entry point and Keen's point was 21.29 ± 16.12 mm. ranging from 0.09 – 74.15 mm. A detailed evaluation of the computer simulation is shown in Table 2.

Table 2 Evaluation in Computer

The results of the ventricular catheter location and the majority of ventricular catheters in a computer simulation, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 100 samples (50 cases, both sides). The shaded box represents the proper location.

Pt	Age Sex	FH ratio	Evan	Side	VPSEAR			Result Location			Keen Majority cath in
					Length (cm)	Result Location	Majority cath in	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
1	48F	0.43	0.36	L	62	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
				R	62	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
2	68M	0.42	0.36	L	66	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
				R	66	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
3	73F	0.42	0.37	L	71	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	73	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
4	73F	0.35	0.31	L	63	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	61	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
5	80F	0.34	0.30	L	61	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Ipsilateral body	Brain
				R	68	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Septum	Ventricle
6	70F	0.37	0.32	L	61	Ipsilateral body	Ventricle	Brain	Third ventricle	Third ventricle	Brain
				R	66	Ipsilateral body	Ventricle	Brain	Brain	Third ventricle	Brain
7	67M	0.43	0.36	L	67	Ipsilateral body	Ventricle	Brain	Third ventricle	Brain	Brain
				R	68	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
8	82F	0.36	0.31	L	64	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
				R	63	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
9	29M	0.63	0.58	L	72	Third ventricle	Ventricle	Brain	Third ventricle	Third ventricle	Brain
				R	68	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
10	82F	0.41	0.33	L	65	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	60	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle

Table 2 (cont.) Evaluation in Computer
The results of the ventricular catheter location and the majority of ventricular catheters in a computer simulation, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 100 samples (50 cases, both sides). The shaded box represents the proper location.

Pt	Age Sex	FH ratio	Evan	Side	VPSEAR			Result Location			Keen Majority cath in
					Length (cm)	Result Location	Majority cath in	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
11	69F	0.43	0.33	L	63	Ipsilateral body	Ventricle	Ipsilateral body	contralateral body	Brain	Ventricle
				R	61	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
12	6F	0.44	0.39	L	65	Ipsilateral body	Ventricle	Ipsilateral body	Brain	Brain	Brain
				R	62	Ipsilateral body	Ventricle	Brain	Brain	contralateral body	Brain
13	72F	0.44	0.39	L	69	Ipsilateral body	Ventricle	Brain	Brain	contralateral body	Brain
				R	70	Ipsilateral body	Ventricle	Brain	Brain	Brain	Brain
14	63F	0.43	0.39	L	66	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	61	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
15	46F	0.47	0.39	L	64	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Septum	Ventricle
				R	69	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
16	52F	0.49	0.39	L	56	Ipsilateral body	Ventricle	Brain	Ipsilateral body	contralateral body	Ventricle
				R	63	Brain	Brain	Ipsilateral body	Third ventricle	Brain	Ventricle
17	54F	0.48	0.39	L	63	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
				R	60	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Septum	Ventricle
18	82M	0.49	0.41	L	62	Ipsilateral body	Ventricle	contralateral body	contralateral body	contralateral body	Ventricle
				R	59	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
19	16F	0.46	0.38	L	68	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	70	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
20	67F	0.35	0.28	L	64	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body body	Ipsilateral body	Ventricle
				R	60	Ipsilateral body	Ventricle	Ipsilateral body	Brain	contralateral body	Brain

Table 2 (cont.) Evaluation in Computer

The results of the ventricular catheter location and the majority of ventricular catheters in a computer simulation, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 100 samples (50 cases, both sides). The shaded box represents the proper location.

Pt	Age Sex	FH ratio	Evan	Side	VPSEAR			Result Location			Keen Majority cath in
					Length (cm)	Result Location	Majority cath in	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
21	80F	0.38	0.31	L	72	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Brain
				R	75	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
22	72M	0.48	0.39	L	65	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	66	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Ipsilateral body	Ventricle
23	76F	0.41	0.35	L	63	Brain	Brain	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	63	Brain	Brain	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
24	19M	0.41	0.32	L	60	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	65	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
25	75F	0.48	0.36	L	37	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
				R	44	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
26	36F	0.38	0.32	L	75	Ipsilateral body	Ventricle	Brain	Brain	Third ventricle	Brain
				R	71	Brain	Brain	Ipsilateral body	Brain	Brain	Brain
27	54F	0.48	0.37	L	56	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
				R	63	Ipsilateral body	Ventricle	Brain	Third ventricle	Third ventricle	Ventricle
28	46F	0.43	0.36	L	99	Brain	Brain	Ipsilateral body	Brain	contralateral body	Ventricle
				R	92	Contralateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
29	66F	0.36	0.32	L	61	Ipsilateral body	Ventricle	Ipsilateral body	contralateral body	contralateral body	Ventricle
				R	72	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
30	85F	0.40	0.33	L	74	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Ipsilateral body	Ventricle
				R	76	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Ipsilateral body	Ventricle

Table 2 (cont.) Evaluation in Computer
The results of the ventricular catheter location and the majority of ventricular catheters in a computer simulation, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 100 samples (50 cases, both sides). The shaded box represents the proper location.

Pt	Age Sex	FH ratio	Evan	Side	VPSEAR			Result Location			Keen Majority cath in
					Length (cm)	Result Location	Majority cath in	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
31	55F	0.35	0.28	L	83	Contralateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	88	Contralateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
32	18F	0.3	0.28	L	45	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
				R	54	Ipsilateral body	Ventricle	Third ventricle	Third ventricle	Brain	Ventricle
33	64M	0.39	0.34	L	69	Ipsilateral body	Ventricle	Brain	Third ventricle	Brain	Brain
				R	71	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
34	54F	0.38	0.30	L	63	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	65	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
35	56F	0.47	0.38	L	46	Ipsilateral body	Ventricle	Ipsilateral body	contralateral body	contralateral body	Ventricle
				R	53	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
36	45F	0.38	0.30	L	65	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Lateral wall of lateral vent	Ventricle
				R	60	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
37	72M	0.42	0.34	L	68	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	75	Brain	Brain	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
38	75F	0.37	0.31	L	46	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	contralateral body	Ventricle
				R	56	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	contralateral body	Ventricle
39	83F	0.24	0.26	L	72	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	76	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
40	86F	0.38	0.31	L	58	Ipsilateral body	Ventricle	Ipsilateral body	contralateral body	Lateral wall of lateral vent	Ventricle
				R	48	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle

Table 2 (cont.) Evaluation in Computer
The results of the ventricular catheter location and the majority of ventricular catheters in a computer simulation, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 100 samples (50 cases, both sides). The shaded box represents the proper location.

Pt	Age Sex	FH ratio	Evan	Side	VPSEAR			Result Location			Keen Majority cath in
					Length (cm)	Result Location	Majority cath in	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
41	60M	0.45	0.37	L	62	Ipsilateral body	Ventricle	Ipsilateral body	Septum	contralateral body	Ventricle
				R	83	Ipsilateral body	Ventricle	Ipsilateral body	contralateral body	contralateral body	Ventricle
42	23F	0.39	0.32	L	62	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	63	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
43	88M	0.38	0.30	L	85	Third ventricle	Ventricle	Ipsilateral body	Third ventricle	Lateral wall of lateral vent	Ventricle
				R	79	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
44	65M	0.35	0.30	L	51	Ipsilateral body	Ventricle	Septum	contralateral body	Lateral wall of lateral vent	Ventricle
				R	62	Brain	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
45	66F	0.35	0.27	L	63	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	contralateral body	Ventricle
				R	38	Brain	Brain	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
46	71M	0.42	0.34	L	56	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	54	Brain	Brain	Ipsilateral body	Third ventricle	contralateral body	Ventricle
47	78M	0.36	0.30	L	73	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	79	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
48	47F	0.42	0.35	L	58	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
				R	59	Ipsilateral body	Ventricle	Ipsilateral body	Third ventricle	Brain	Ventricle
49	90M	0.33	0.27	L	79	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Ipsilateral body	Ventricle
				R	78	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	Septum	Ventricle
50	72F	0.32	0.29	L	54	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
				R	62	Ipsilateral body	Ventricle	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle

Abbreviation: FH=frontal horn

VPSEAR Evaluation in 3D Skull Models Simulation

Thirty samples of fifteen 3D skull models were evaluated. The proper location of the ventricular catheter was achieved in the same number by computer simulation in the VPSEAR group (96.67%). Only one case (Case. No.9, left side) showed a improper location in the third ventricle (Figure 5, red asterisk). Keen's point evaluation also showed the same accuracy as a computer simulation. The angle of deviation from the theoretical perpendicular trajectory was 8.64 ± 3.38 degrees, ranging from 3.33 to 16.63 degrees. Detailed 3D skull model evaluation is shown in Table 3 and Figure 5.

Table 3 Evaluation in Phantoms

The results of the ventricular catheter location, the majority of ventricular catheters and angle deviation from the theoretical perpendicular trajectory, according to the recommended ventricular lengths of the VPSEAR entry point and different ventricular lengths of Keen's point in 30 samples (15 cases of 3D skull model, both sides). The shaded box represents the proper location.

Pt	Age	Side	VP SEAR (Phantom)			Result Location (Phantom)			Keen Majority cath in
Sex			Result Location	Majority cath in	Angle deviation	Keen length 6 cm	Keen length 7 cm	Keen length 8 cm	
1	48F	L	Ipsilateral body	Ventricle	11.17	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
		R	Ipsilateral body	Ventricle	7.63	Ipsilateral body	Third ventricle	Brain	Ventricle
2	68M	L	Ipsilateral body	Ventricle	4.23	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
		R	Ipsilateral body	Ventricle	5.5	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
3	73F	L	Ipsilateral body	Ventricle	7.2	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
		R	Ipsilateral body	Ventricle	6.37	Ipsilateral body	Septum	contralateral body	Ventricle
4	73F	L	Ipsilateral body	Ventricle	7.07	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
		R	Ipsilateral body	Ventricle	6.37	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
5	80F	L	Ipsilateral body	Ventricle	10.77	Ipsilateral body	Ipsilateral body	Ipsilateral body	Brain
		R	Ipsilateral body	Ventricle	12.5	Ipsilateral body	Ipsilateral body	Septum	Ventricle
6	70F	L	Ipsilateral body	Ventricle	9.17	Brain	Third ventricle	Third ventricle	Brain
		R	Ipsilateral body	Ventricle	9.77	Brain	Brain	Third ventricle	Brain
7	67M	L	Ipsilateral body	Ventricle	8.57	Brain	Third ventricle	Brain	Brain
		R	Ipsilateral body	Ventricle	7.97	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
8	82F	L	Ipsilateral body	Ventricle	10.4	Ipsilateral body	Third ventricle	Brain	Ventricle
		R	Ipsilateral body	Ventricle	11.93	Ipsilateral body	Third ventricle	Brain	Ventricle
9	29M	L	Third ventricle	Ventricle	12.63	Brain	Third ventricle	Third ventricle	Brain
		R	Ipsilateral body	Ventricle	4.17	Ipsilateral body	Third ventricle	Third ventricle	Ventricle
10	82F	L	Ipsilateral body	Ventricle	3.33	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
		R	Ipsilateral body	Ventricle	4.2	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
11	69F	L	Ipsilateral body	Ventricle	14.3	Ipsilateral body	contralateral body	Brain	Ventricle
		R	Ipsilateral body	Ventricle	8.7	Ipsilateral body	Third ventricle	Brain	Ventricle
12	6F	L	Ipsilateral body	Ventricle	3.47	Ipsilateral body	Brain	Brain	Brain
		R	Ipsilateral body	Ventricle	16.63	Brain	Brain	contralateral body	Brain
13	72F	L	Ipsilateral body	Ventricle	8.23	Brain	Brain	contralateral body	Brain
		R	Ipsilateral body	Ventricle	8.03	Brain	Brain	Brain	Brain
14	63F	L	Ipsilateral body	Ventricle	13.43	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
		R	Ipsilateral body	Ventricle	11.53	Ipsilateral body	Ipsilateral body	contralateral body	Ventricle
15	46F	L	Ipsilateral body	Ventricle	7	Ipsilateral body	Ipsilateral body	Septum	Ventricle
		R	Ipsilateral body	Ventricle	7.07	Ipsilateral body	Septum	contralateral body	Ventricle

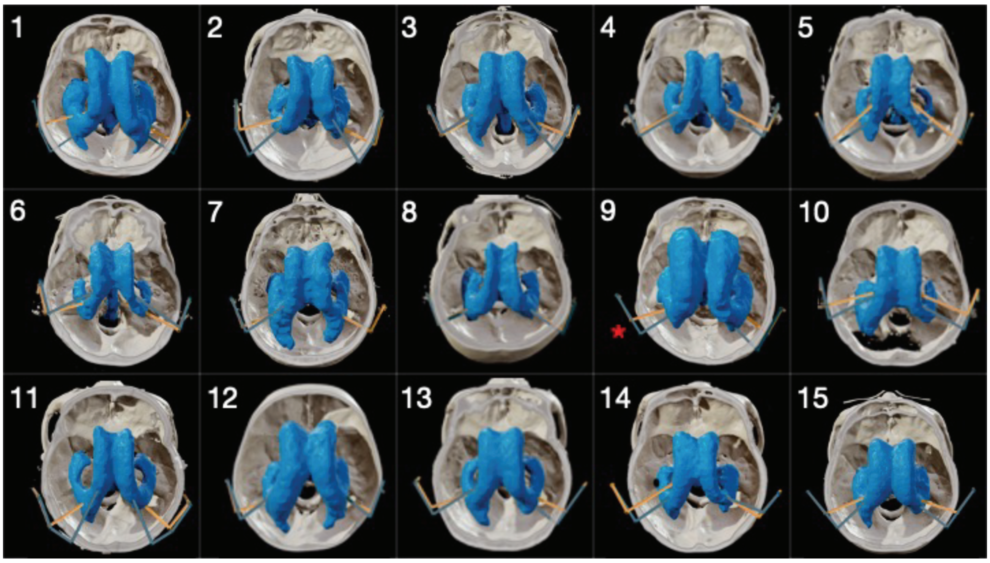

Figure 5 Result of 3D skull model simulation in 15 cases. Blue trajectories represented VPSEAR and orange trajectories represented Keen's point. Red asterisk marked left side of Case No.9 which was the only case in which VPSEAR showed an improper location.

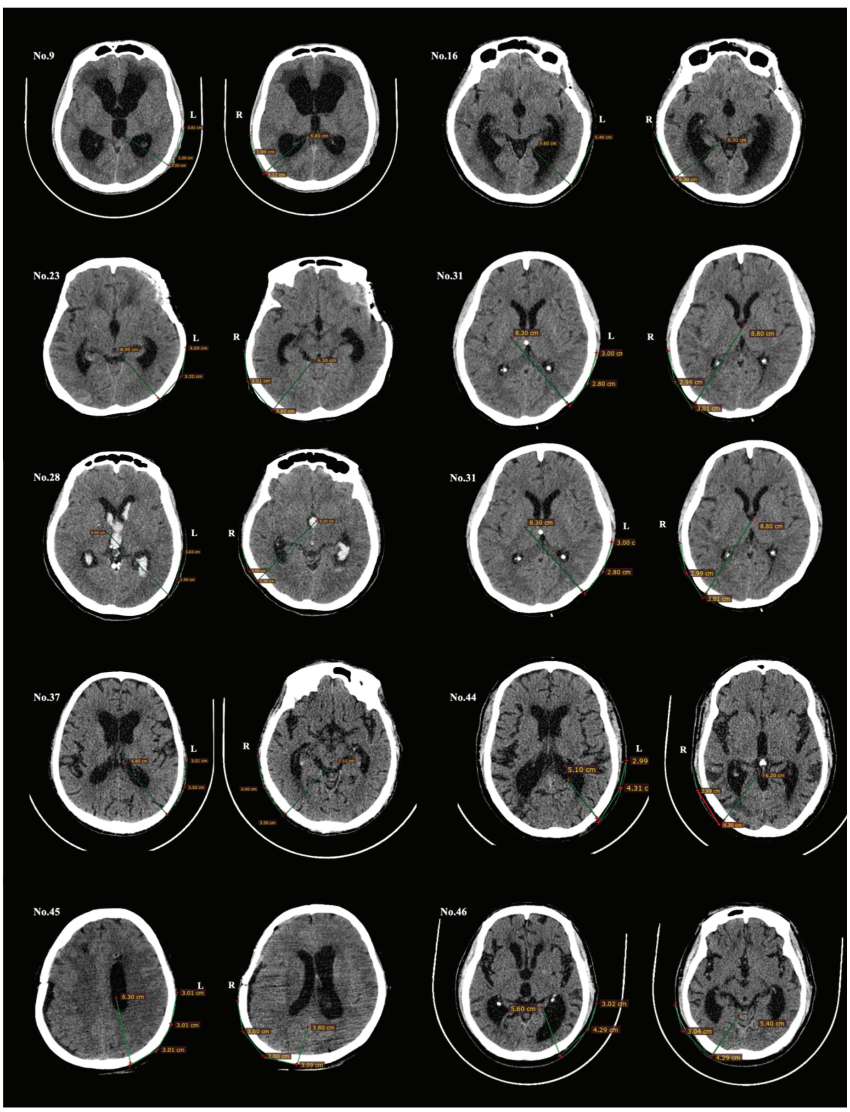

Figure 6 Result of "Improper position" in computer simulation in 14 sample of case No 9, 16, 23, 26, 31, 37, 44, 45, 46 L=Left, R=Right

Table 4 Result of VPSEAR evaluation

Variable	N=50		
VPSEAR ventricular catheter length (mm.)	64.92 ± 10.21 (37-99)		
Displacement between the VPSEAR and Keen's point (mm.)	21.29 ± 16.12 (0.09 – 74.1)		
Angle of deviation (degrees)	8.64 ± 3.38		
Proper location of ventricular tip	VPSEAR	Keen's point	
	86%	Keen length 6 cm	86%
		Keen length 7 cm	46%
		Keen length 8 cm	6%
The majority of catheters were in the ventricle	92%	86%	

Discussion

Even though VP shunt is one of the most commonly performed procedures in neurosurgery, improving outcomes is still challenging because of possible postoperative infection and shunt malfunction.[14,15] The accuracy of ventricular catheter insertion is thought to be related to the operation outcome.[9,11,13] For the past century, ventricular catheters have been inserted by the free-hand technique, using surface anatomical landmarks, but this method is not highly accurate due to aforementioned reasons. The navigator-assisted technique is considered the most accurate but is unavailable in every neurosurgical center.[3,4]

This situation has driven us to create a new option to help guide entry more accurately in individual patients using computer calculations. We believed that optimal ventricular entry is not the same for each patient because their anatomies and degrees of hydrocephalus differ. Similarly, ventricular catheter length should be different in every patient. Improper length of ventricular catheter was found to be related to an improper location and worse outcome.[16] Our study also found that fewer proper location cases were observed with the longer ventricular catheter length used in Keen's point. VP shunt entry and ventricular catheter length should be individualized. For this reason, we developed VPSEAR as an inexpensive tool to help locate proper entry and suggest appropriate ventricular catheter length. We combined neurosurgery knowledge with computer image processing under the cooperation between doctors and programmers to create this integrative and easy-to-use innovation. Our program needs only thin-slice DICOM for input, and a short time to process and report, even during the general anesthesia induction period before surgery, is enough. Moreover, the VPSEAR user interface is developed to be user-friendly.

We chose two methods to evaluate our VPSEAR accuracy: 1. simulation by a computer program using Radiant® and 2. simulation in 3D skull models. We proposed an easily reproducible method to simulate ventricular catheter placement at Keen's point, which could be applied to any entries. Our VPSEAR showed accuracy in ventricular catheter tip location compared to Keen's point with 6, 7 and 8 cm. catheter length computer simulations (86% vs 86%, 46%, 6%, respectively). This result was better accuracy in 3D skull model simulations (96.67%), which we believed would show real-life ventricular puncture. Even though we found the average angle of deviation from the theoretical perpendicular trajectory was 8.64 ± 3.38 degrees due to the surgeon's hand, the outcome of the proper location of the ventricular catheter was still the same. This result implies that our program should be applied to real circumstances. However, fourteen samples showed an improper location for several reasons. First, our VPSEAR could not identify the exact ventricle in some cases. VPSEAR creates the point for ventricular puncture by detecting the surfaces of the skull, lateral ventricles, and the ear pinna, which were constructed from their HU. So, if there are any confounders to their HU, such as marked IVH, EVD skin tract, or subgaleal collection, this could let the program misunderstand as the ventricle instead. Second, cases with improper reference point anatomy, such as the distorted top of the ear pinna, will also obscure the identification of the exact reference point, which affects the entry point and trajectory.

In the real situation, the ventricular catheter is not rigid and straight, but it has some ability to bend and curve. Therefore, after obtaining CSF, while entering a ventricle, the ventricular catheter is inserted gradually and could bend slightly and curve freely in the ventricle, not remain straight like in our simulation, which was not the same as a real ventricular catheter placement. For this reason, our result in ventricular catheter tip location might not be the true representative. Moreover, some may also argue that in real life, we can insert a ventricular catheter more than once, at different angles, to find the ventricle and obtain CSF. Nevertheless, we believe better entry and trajectory and fewer brain penetrations are safer and proper.

Our study had several limitations. First, this was a laboratory study. Second, only Keen's point could be used in the program. Third, this is the first version of our VPSEAR, which creates the point for ventricular puncture with compelling temporalis avoidance. However, the next version of VPSEAR will adapt for other entries and adjust the new algorithm of entry points by focusing only on the bone at the lateral side of the skull region to evaluate the accuracy of VPSEAR.

Conclusion

Our VPSEAR is a promising, inexpensive option for locating ventricular entry points using computer science and neurosurgery knowledge. VPSEAR showed higher accuracy than Keen's point in both computer simulation and 3D skull model simulation for evaluation.

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