·数智神经外科学·

增强现实技术在颅底肿瘤和脑血管病手术中的应用

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【摘要】 **研究背景** 计算机技术和人工智能技术的发展使数智神经外科学日趋成熟,增强现实技术作为新兴技术已在神经外科手术中展现出巨大潜力,探讨该项技术辅助神经外科手术的可行性和实用性将是现阶段临床研究的重要议题。**方法** 纳入4例2024年1-12月在清华大学附属北京清华长庚医院行神经外科手术的前庭神经鞘瘤(1例)、颅内动脉瘤(2例)和锁骨下动脉闭塞致椎动脉盗血综合征(1例)患者,分别接受前庭神经鞘瘤切除术、颈内动脉-后交通动脉动脉瘤夹闭术和颈总动脉(CCA)-锁骨下动脉(SA)搭桥术;将术前常规影像学数据导入Surgical AR软件,基于HoloLens 2平台进行术前规划、模拟手术和术中实时显示,并与实际手术操作和术后影像学数据对比,定性分析增强现实技术辅助神经外科手术的疗效。**结果** (1)前庭神经鞘瘤切除术:与术前增强现实技术模拟手术(模拟手术)对比,实际手术完全复现经枕下乙状窦后入路开颅、内耳道后壁磨除、内耳道内肿瘤显露和切除的操作过程,术中面神经保护完好,术后面神经功能达House-Brackmann分级Ⅰ级,但未保留有效听力;术后1周三维重建CT与术前模拟和术中实际所见无明显差异;术后6个月改良Rankin量表(mRS)评分为2分。(2)颈内动脉-后交通动脉动脉瘤夹闭术:与术前模拟手术对比,实际手术完全复现经眶上外侧入路开颅、磨除前床突、显露动脉瘤颈并夹闭的手术过程;术后三维重建CTA与术前模拟无明显差异;术后6个月,眼部胀痛、上睑下垂、复视等症状完全缓解,mRS评分为零。(3)基底动脉尖动脉瘤夹闭术:根据术前模拟结果,经眶颧入路对动脉瘤颈的显露更充分且术者可于直视下完全夹闭动脉瘤并保护双侧大脑后动脉P1段,操作安全性明显优于经颞下入路;实际手术中选择经眶颧入路,分离外侧裂经颈内动脉-动眼神经间隙显露基底动脉和动脉瘤、夹闭动脉瘤;术后6个月mRS评分为零,动眼神经功能恢复良好。(4)CCA-SA搭桥术:术中通过增强现实技术辅助颈部重要肌肉、血管体表定位,充分显露颈总动脉和锁骨下动脉,人工血管吻合;术后三维重建CTA显示桥血管通畅;患者头晕症状未再发作,患侧上肢血压恢复正常;术后6个月mRS评分为零。**结论** 增强现实技术用于神经外科手术可术前手术规划、手术模拟和术中引导,有助于青年医师快速理解复杂的解剖结构、缩短学习曲线,具有重要的临床价值和广阔的应用前景。

【关键词】 增强现实; 颅底肿瘤; 颅内动脉瘤; 神经外科手术

Application of augmented reality technology in the surgery of skull base tumor and cerebrovascular disease

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doi:10.3969/j.issn.1672-6731.2025.03.008

基金项目:国家自然科学基金资助项目(项目编号:U20A20389);清华大学精准医学科研计划战略项目(项目编号:2022ZLB007);清华大学附属北京清华长庚医院研究者发起研究项目(项目编号:12024Z01017)

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【Abstract】 **Background** Neurosurgery developed rapidly with technology advancing. Concept of digit-intelligent neurosurgery becomes mature and augmented reality (AR) technology shows great potential in future neurosurgical operations. The feasibility and applicability of AR assisted technology is currently the most important topic in clinical research. **Methods** Four cases engaged from January to December 2024 in Department of Neurosurgery of Beijing Tsinghua Changgung Hospital with vestibular schwannoma (one case), intracranial aneurysm (2 cases) and subclavian artery (SA) occlusion caused vertebral artery steal syndrome (one case) have been conducted tumor resection, internal carotid artery (ICA) - posterior communicating artery (PCoA) aneurysm clipping and common carotid artery (CCA)-SA bypass, respectively. Using presurgical imaging data-based Surgical AR reconstruction on the HoloLens 2 platform, preoperative planning, surgical simulation, and intraoperative display were conducted. These were then compared with surgical practices and postoperative imaging data to qualitatively evaluate their effectiveness in assisting neurosurgery. **Results** 1) Vestibular schwannoma resection: compared to the preoperative AR assisted simulation, we fully replicated the procedures of retrosigmoid approach craniotomy, removal of the posterior wall of internal auditory canal, and the exposure and removal of the internal auditory canal tumor during surgical practice. Facial nerve function was preserved intact during the surgery and reached House-Brackmann grade Ⅰ, but effective hearing was not preserved. Postoperative imaging data showed non-significant difference compared to preoperative simulation and surgical practice. The modified Rankin Scale (mRS) assessed postoperatively was 2. 2) ICA-PCoA aneurysm clipping: compared to the presurgical AR assistance, we fully replicate the procedures of lateral supraorbital craniotomy, removal of anterior clinoid process and the exposure and clipping of the neck of aneurysm. Postoperative imaging data showed non-significant difference compared to preoperative simulation. Postoperatively symptoms such as eye pain, ptosis, and double visian were completely relieved and the mRS was 0 after 6 months. 3) Basilar artery apex aneurysm clipping: based on preoperative simulation, we opted for the orbito-zygomatic approach during surgery to provide full exposure of the aneurysm neck and direct visualization of the bilateral P1 segment of posterior cerebral artery (PCA), offering better safety compared to the subtemporal approach. In surgical practice, lateral sulcus was separated, basilar artery and aneurysm was exposed and clipped via carotid spaces. Postoperatively occlomoter nerve was well recovered mRS was 0 after 6 months. 4) CCA-SA bypass: critical muscles and vessels on the neck were located intraoperatively on the body surface with AR assistance. CCA and SA were fully exposed and artificial vessel was anastomosed. Postoperative CTA 3D reconstruction suggested the blood flow was patent. The dizziness did not recur, and the blood pressure in the upper limb on the affected side returned to normal. Postoperative mRS was 0 after 6 months. **Conclusions** The application of AR technology in neurosurgical procedures allows for preoperative planning, surgical simulation, and intraoperative display. It aids young surgeons in quickly understanding complex anatomical structures and shortens the learning curve, holding significant clinical value and promising application prospects.

【Key words】 Augmented reality; Skull base neoplasms; Intracranial aneurysm; Neurosurgical procedures

This study was supported by the National Natural Science Foundation of China (No. U20A20389), Strategic Project of Precision Medicine Research Program of Tsinghua University (No. 2022ZLB007), and Beijing Tsinghua Changgung Hospital Fund (IIT Program, No. 12024Z01017).

Conflicts of interest: none declared

神经外科学从经典神经外科学、显微神经外科学至今日的微侵袭神经外科学历经百年，发展迅速。自21世纪以来，随着计算机技术和数据科学的不断发展，人工智能（AI）技术登上历史舞台，神经外科学面临前所未有的发展机遇和挑战。加强计算机技术在神经外科学的应用，以更先进的技术辅助神经外科术前、术中和术后规划和操作[1-2]，是数智神经外科学得以发展的基础[3-4]。目前已有一系列科技产物开始在数智神经外科学中进行研究和初步应用，如增强现实（AR）和人工智能技术辅助更好的术前诊断和手术规划、手术机器人技术辅助更精准的手术操作[5]，其中增强现实技术的应用尤为广泛，主要用于术前规划、术中指导、医师培训等[6]。颅底骨质解剖结构和颅内血管走行复杂，因此对于颅底肿瘤和脑血管病，准确的解剖标志和适宜的手术入路对获得最佳显露至关重要，既往通过示意图、影像学三维重建、尸体解剖及术中照片或视频等提供尽可能翔实的解剖关系，但对于经验较少的青年神经外科医师仍较困难，故在三维渲染的基础上增加增强现实模拟器可能成为有价值的方法。

清华大学附属北京清华长庚医院在前庭神经鞘瘤切除术、颅内动脉瘤夹闭术和颈总动脉(CCA)-锁骨下动脉(SA)搭桥术中，基于增强现实技术进行个性化治疗，显著减少手术创伤、改善患者预后，现总结报告如下。

对象与方法

一、研究对象

1. 纳入与排除标准 (1)诊断明确的颅底肿瘤和脑血管病患者。(2)需行开颅手术。(3)术前和术中均需配合使用增强现实技术辅助。(4)排除临床资料不完整患者。(5)本研究经清华大学附属北京清华长庚医院伦理委员会审核批准(审批号：24209-4-02)。(6)所有患者及其家属均对手术方案知情并签署知情同意书。

2. 一般资料 根据上述纳入与排除标准，选择2024年1-12月在我院神经外科住院治疗的颅底肿瘤和脑血管病患者共4例，男性1例，女性3例；年龄57～73岁，平均(64.00±12.45)岁。前庭神经鞘瘤患者以听力下降、偶有面部抽动为主要临床表现，House-Brackmann分级Ⅰ级；颅内动脉瘤患者[颈内动脉(ICA)-后交通动脉(PCoA)动脉瘤和基底动脉尖动脉瘤各1例]均以自发性蛛网膜下腔出血入院，颈内动脉-后交通动脉动脉瘤患者同时伴有眼部胀痛、上睑下垂、复视，但无视力下降，Hunt-Hess分级Ⅰ级，基底动脉尖动脉瘤患者Hunt-Hess分级Ⅲ级；锁骨下动脉闭塞致椎动脉盗血综合征患者主要表现为发作性头晕，其患侧上肢血压为91/70 mm Hg (1 mm Hg＝0.133 kPa)、健侧为153/88 mm Hg。

二、研究方法

1. 影像学数据采集 所有患者手术前后均行CT和MRI增强扫描，脑血管病患者同时行头颈部CTA检查。(1)CT：采用德国Siemens公司生产的SOMATO CT扫描仪，患者仰卧位，骨窗算法重建，窗位2600 HU、窗宽800 HU、层厚为5 mm、层间距为0.625 mm，软组织算法重建，窗位为80 HU、窗宽为35 HU、层厚5 mm、层间距0.625 mm，共扫描223层。(2)MRI：采用美国GE公司生产的GE MR750 3.0T MRI扫描仪，患者仰卧位，行矢状位3D-T_1WI增强扫描。检查前30 min静脉注射钆对比剂0.20 ml/kg，扫描参数为重复时间(TR)400 ms、回波时间(TE)为10 ms、反转时间(TI)500 ms，翻转角(FA)90°，扫描视野(FOV)256 mm×256 mm，矩阵256×256，激励次数(NEX)1次，层厚1 mm、层间距为零，扫描时间30 min，共176层。(3)CTA：采用德国Siemens公司生产的SOMATO CT扫描仪。扫描前禁食4 h，静脉注射碘对比剂，注射速度5 ml/s，共50 ml；扫描参数为窗宽400 HU、窗位35 HU，层厚3 mm、层间距为0.625 mm；图像后处理行最大密度投影(MIP)和容积重建(VR)。

2. 三维模型重建 增强现实技术显示于头戴式HoloLens 2平台(美国Microsoft公司)，搭载Windows 10操作系统。CT、MRI和CTA原始影像学数据均采取DICOM格式，导入HoloLens 2平台，采用Surgical AR软件(美国Medvis公司)行三维模型重建，辅助术者进行术前规划、模拟手术和术中实时显示。

3. 增强现实技术辅助手术治疗 (1)前庭神经鞘瘤切除术：经右侧枕下乙状窦后入路切除肿瘤。术前采用增强现实技术行术前规划和模拟手术，在增强现实技术辅助下，于手术体位采用Surgical AR软件ERASE工具在CT重建的三维骨性结构模型上模拟枕下乙状窦后入路开颅手术，切除右侧枕骨鳞部，观察内耳道，磨除内耳道后壁；再将MRI重建的三维头部模型同样采用ERASE工具模拟开颅手术，显露脑池段肿瘤，磨除内耳道后壁，直至满意显露内耳道内增强的肿瘤全息图像，测量磨除范围。实际手术中患者左侧卧位，经右侧枕下乙状窦后入路，显微镜下切开硬脑膜，开放枕大池充分释放脑脊液，小脑组织松弛塌陷后显露脑池段肿瘤和内耳道口，按照术前模拟手术计划以超声骨刀磨除内耳道后壁，充分显露内耳道内肿瘤，全切除肿瘤，完好保护面神经。(2)颈内动脉-后交通动脉动脉瘤夹闭术：行左侧眶上外侧入路动脉瘤夹闭术。因动脉瘤颈被前床突骨性结构遮挡，术前采用增强现实技术行术前规划和模拟手术，于手术体位下采用ERASE工具在CTA重建的三维模型上模拟开颅手术，磨除前床突，显露动脉瘤。实际手术中患者仰卧位，头部转向健侧30°，经左侧眶上外侧入路，显微镜下开放鞍上池，充分释放脑脊液，显露左颈内动脉床突上段和动脉瘤，磨除前床突，充分显露动脉瘤颈，夹闭动脉瘤。(3)基底动脉尖动脉瘤夹闭术：行右侧眶颧入路动脉瘤夹闭术。术前采用增强现实技术行术前规划和模拟手术，在CTA重建的三维模型上对比经眶颧入路与经颞下入路这两种手术入路对动脉瘤颈的显露范围。实际手术中患者仰卧位，经右

侧眶颧入路行单骨瓣开颅手术，术中分离外侧裂经颈内动脉-动眼神经间隙显露基底动脉（BA）和动脉瘤，夹闭动脉瘤。（4）CCA-SA搭桥术：患者为左锁骨下动脉近心端闭塞致同侧椎动脉盗血综合征，术前采用增强现实技术在CTA重建的三维模型上行术前规划和模拟手术，术中根据CTA数据实时注册，将3D渲染的全息解剖结构映射至患者，定位锁骨下动脉闭塞部位及其局部解剖如颈部重要肌肉、血管体表关系，设计体表手术切口。实际手术中患者仰卧位，做左侧锁骨上横切口，充分显露颈总动脉和锁骨下动脉，采用人工血管行CCA-SA搭桥术。

4.评价指标 （1）前庭神经鞘瘤：术后观察患者症状改善，根据House-Brackmann分级观察面神经功能改善程度；术后1周内复查CT，比较术前增强现实技术模拟手术与实际手术流程和操作以及与术后内耳道实际磨除的相似程度。（2）颈内动脉-后交通动脉动脉瘤：术后1周内复查CTA，比较术前模拟手术与实际手术流程和操作过程以及与术后三维重建CTA模型的相似程度。（3）基底动脉尖动脉瘤：比较术前模拟的两种手术入路与实际手术采用的手术入路。（4）CCA-SA搭桥术：术后观察患者症状改善；术后1周内复查CTA，观察桥血管是否通畅。（5）随访：所有患者均于术后6个月采用改良Rankin量表（mRS）评估临床预后，mRS评分≤2分为预后良好、>2分为预后不良。

结 果

一、术前增强现实技术可以精准模拟手术过程

本研究前庭神经鞘瘤患者术前模拟的内耳道内肿瘤切除过程包括经枕下乙状窦后入路开颅（图1a）和内耳道后壁磨除（图1b），并模拟手术过程中实现内耳道内肿瘤完全显露（图1c，1d）；实际手术中完全复现术前模拟过程和操作，实现肿瘤及其周围重要解剖结构的充分显露（图1e，1f），术中实际显露与术前模拟无明显差异（图1g）；术中面神经保护完好，术后面神经功能良好，达House-Brackmann分级Ⅰ级（图1h），但未保留有效听力；术后1周三维重建CT与术前模拟和术中实际所见无明显差异（图2）；术后6个月mRS评分2分。颈内动脉-后交通动脉动脉瘤患者术前三维重建CTA显示颈内动脉床突上段动脉瘤被前床突骨性结构遮挡（图3a），通过增强现实技术模拟眶上外侧入路开颅（图3b，3c）和前床突磨除以显露动脉瘤颈（图3d，3e）；实际手术中磨除前床突、充分显露动脉瘤颈与术前模拟手术一致，术中顺利夹闭动脉瘤；术后1周三维重建CTA与术前模拟无明显差异（图3f，3g）；术后6个月，眼部胀痛、上睑下垂、复视等症状完全缓解，提示动眼神经功能恢复，mRS评分为零。临床结果表明，在术前影像学检查基础上进行增强现实技术模拟手术可以提前预演手术操作过程，进而提高现实手术的精准性。

二、术前增强现实技术可以辅助术前规划

本研究基底动脉尖动脉瘤患者经术前三维重建CTA显示动脉瘤位于基底动脉尖（图4a），经增强现实技术模拟对比眶颧入路（图4b，4c）和颞下入路（图4d，4e），提示经颞下入路基底动脉尖动脉瘤夹闭术难以观察到动脉瘤颈对侧，而经眶颧入路则可以充分显露动脉瘤颈的术者侧与术者对侧夹角，术者可于直视下完全夹闭动脉瘤并保护双侧大脑后动脉（PCA）P1段，操作过程更安全；实际手术中采取经眶颧入路，分离外侧裂经颈内动脉-动眼神经间隙显露基底动脉和动脉瘤，完全夹闭动脉瘤（图4f，4g）。术后6个月mRS评分为零，动眼神经功能恢复良好。模拟手术结果提示，术前增强现实技术具有辅助手术规划、选择更优手术路径的作用。

三、增强现实技术可以优化手术操作

本研究锁骨下动脉闭塞致椎动脉盗血综合征患者术前DSA显示左锁骨下动脉闭塞（图5a），遂行CCA-SA搭桥术，术中通过增强现实技术辅助颈部重要肌肉、血管体表定位（图5b～5d），确认最佳手术切口（图5e）、了解目标血管的局部解剖结构和层次并充分显露颈总动脉和锁骨下动脉，采用人工血管进行吻合（图5f）。术后1周三维重建CTA可见桥血管通畅（图5g）；患者头晕症状未再发作，患侧上肢血压恢复正常；术后6个月mRS评分为零。临床结果表明，术中增强现实技术有助于神经外科医师优化手术操作，提高手术效率。

讨 论

随着计算机技术的不断发展及脑科学的不断探索，神经外科学正经历新一轮的变革和创新，以计算机技术和增强现实技术辅助神经外科手术的数智神经外科学的发展尤为突出，目前已出现较多该项技术应用于术前、术中乃至术后临床实践的实例[6-8]。本研究首次采用增强现实技术辅助复杂颅底肿瘤和脑血管病行术前规划和术中处理，以进一

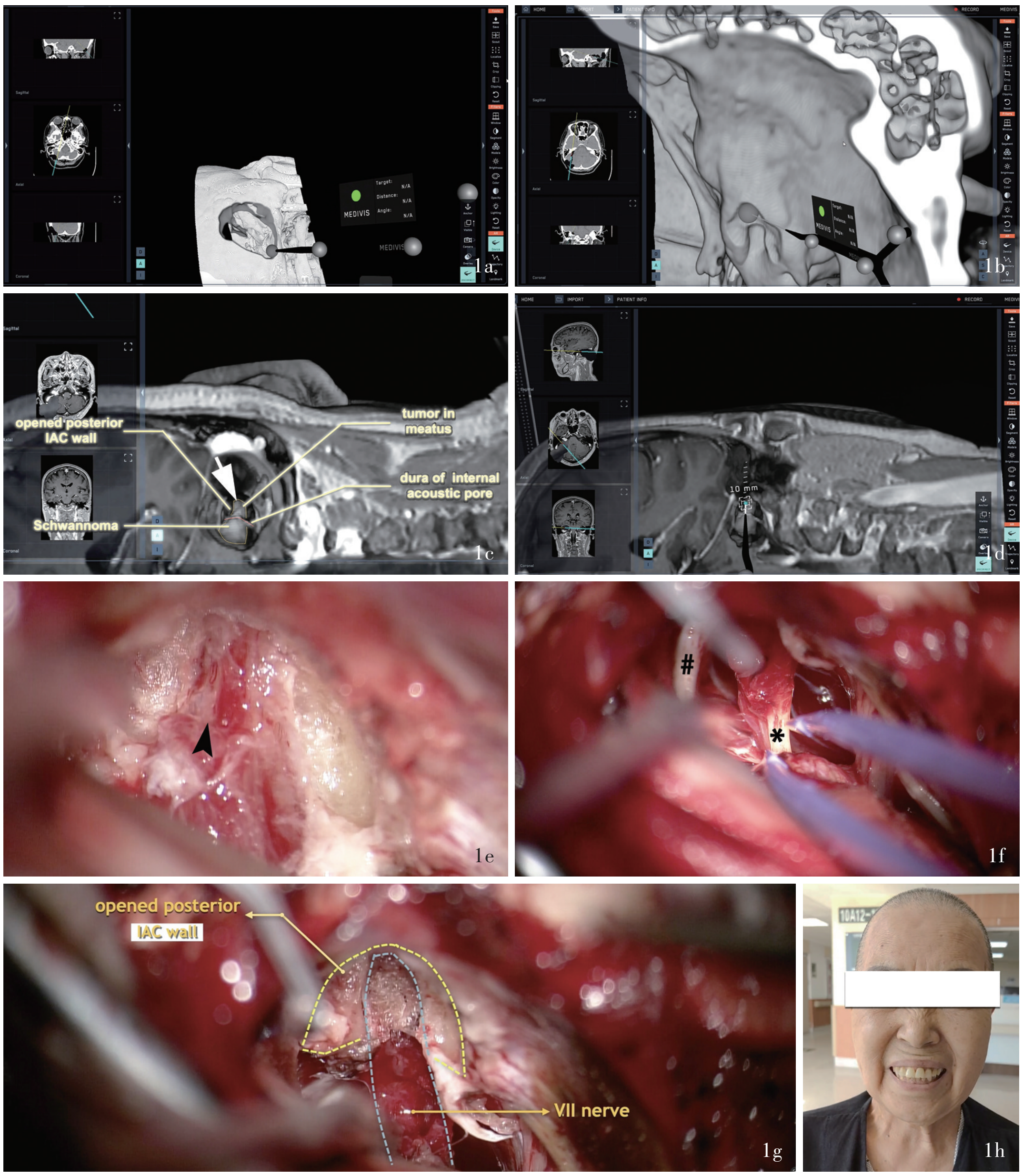

图1　前庭神经鞘瘤术前模拟与实际手术影像对比　1a　术前于三维重建CT的全息影像上模拟经右侧枕下乙状窦后入路开颅手术　1b　术前于三维重建CT的全息影像上模拟磨除内耳道后壁　1c　术前于三维重建MRI的全息影像上模拟磨除内耳道后壁，显露内耳道内肿瘤（箭头所示）　1d　术前于三维重建MRI的全息影像上测量模拟磨除内耳道后壁的骨质范围　1e　实际手术中磨除内耳道后壁后可见内耳道内肿瘤（箭头所示）　1f　术中切除肿瘤后可见面神经（#所示）和三叉神经（*所示）保护完好　1g　术中切除肿瘤后可见磨除的内耳道（黄色虚线所示）和完整的面神经（蓝色虚线所示）　1h　术后面神经功能保留（House-Brackmann分级Ⅰ级）

Figure 1　Comparison of preoperative AR assisted with actual images of vestibular schwannoma neurosurgery Preoperative simulation of right retrosigmoid approach craniotomy via CT 3D reconstruction (Panel 1a). Removal of internal auditory canal posterior wall via CT 3D reconstruction (Panel 1b). Tumor exposed after posterior wall of internal auditory canal simulate removal via MRI 3D reconstruction (arrow indicates, Panel 1c). The range of exposure for internal auditory canal posterior wall after removal (Panel 1d). Intraoperative visualization of tumor after removal of internal auditory canal posterior wall (arrow indicates, Panel 1e). Intraoperative visualization of facial nerve (# indicates) and trigeminal nerve (* indicates, Panel 1f). Intraoperative visualization of opened internal auditory canal (yellow dotted lines indicate) and intact facial nerve (blue dotted lines indicate, Panel 1g). Postoperative facial nerve function was House-Brackmann grade Ⅰ (Panel 1h).

步探究增强现实技术在神经外科手术临床实践中的应用方法和潜在获益。

神经外科手术涉及重要且复杂的颅内解剖结构，操作困难，要求极高的技术和经验。混合现实

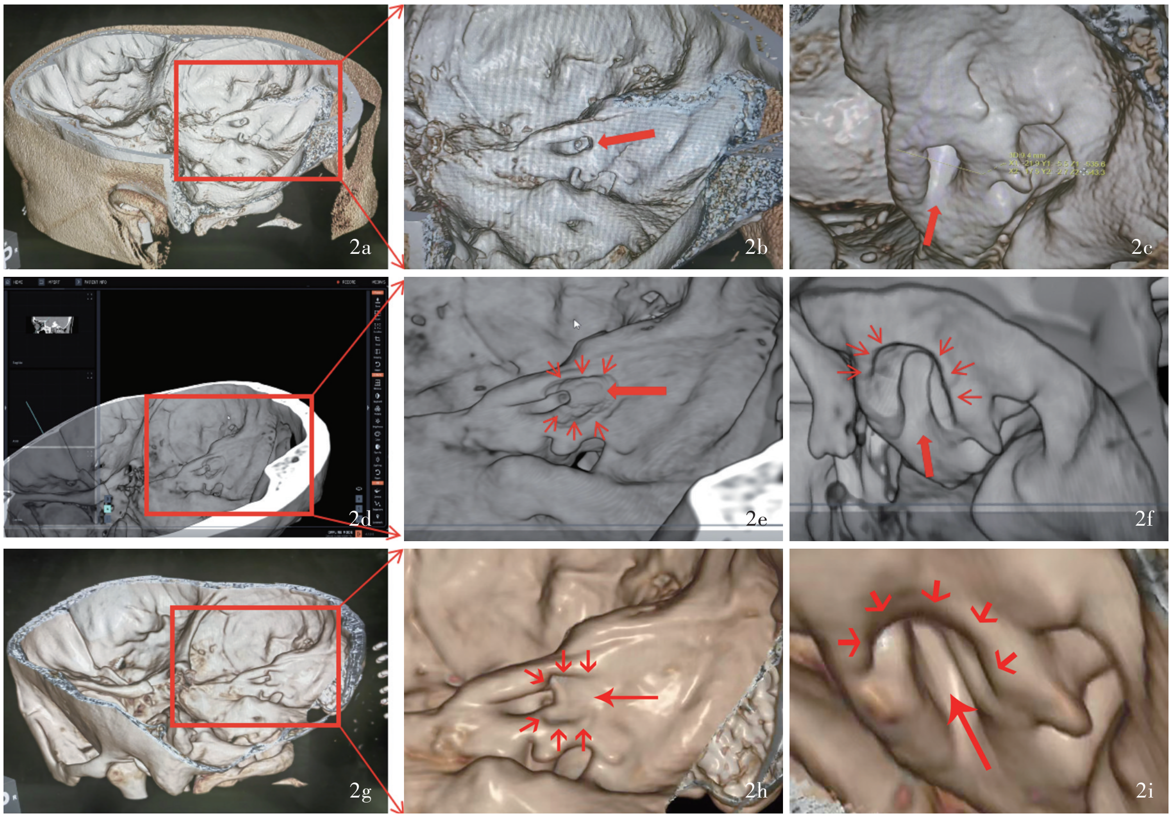

图 2 前庭神经鞘瘤手术前后三维重建 CT 所见 2a～2c 术前三维重建 CT 显示内耳道形状(长箭头所示) 2d～2f 增强现实技术模拟的内耳道磨除范围(短箭头所示) 2g～2i 术后三维重建 CT 显示内耳道形状(长箭头所示)及其后壁实际磨除范围(短箭头所示)

Figure 2 Before and after surgery CT 3D reconstruction findings of vestibular schwannoma Preoperative CT 3D reconstruction showed internal auditory canal (long arrows indicate, Panel 2a-2c). The range of AR assisted of internal auditory canal removal (short arrows indicate, Panel 2d-2f). Postoperative CT 3D reconstruction showed internal auditory canal (long arrows indicate) and posterior wall acutal removal range (short arrows indicate, Panel 2g-2i).

(MR)技术在神经外科的应用主要是辅助术前和术中重要解剖结构定位并指导术中操作[9-10]，增强现实技术辅助下可以进行更详细、更个性化的术前手术规划，优化术中操作。颅底解剖结构复杂，神经外科手术中常见颅底骨性结构、血管、神经遮挡病变，增强现实技术辅助颅底肿瘤手术主要体现在术前模拟手术以精准定位和显露病变，辅助脑血管病手术主要体现在术中显微镜下实时显示以提高对三维解剖结构的认识[11-12]。本研究采用增强现实技术可视化规划不同手术入路，如乙状窦后入路切除前庭神经鞘瘤，眶上外侧入路夹闭颈内动脉-后交通动脉动脉瘤，眶颧入路夹闭基底动脉尖动脉瘤等，并直接模拟术中重要操作步骤和难点部分，从而更好地对手术流程和操作进行规划。前庭神经鞘瘤切除术中磨除内耳道后壁是显露内耳道内肿瘤并实现全切除的重要步骤，增强现实技术可在术前模拟磨除内耳道后壁，一方面使术者提前对颅内操作时面临的情况有直观感受，另一方面通过模拟探索出实现最大程度显露肿瘤和最小程度损伤走行于内耳道内面神经的内耳道后壁磨除流程[13]。该应用同样适用于颅内动脉瘤手术中模拟磨除前床突及眶颧入路模拟磨除颅底骨质等操作。更大范围的增强现实技术应用探索以及更大样本量的术前和术中应用实例有待进一步探索。本研究通过定性分析增强现实技术在颅底肿瘤和脑血管病手术中的作用，发现其可以有效辅助神经外科医师进行术前模拟、术中规划和引导，对神经外科手术有重大意义和丰富的潜在应用前景。

增强现实技术在神经外科医师培训中也起到重要作用[14-15]。神经外科医师培养困难，主要原因是大脑解剖结构复杂、功能重要，对手术技术的要求极高。既往有各项技术在神经外科手术模拟和

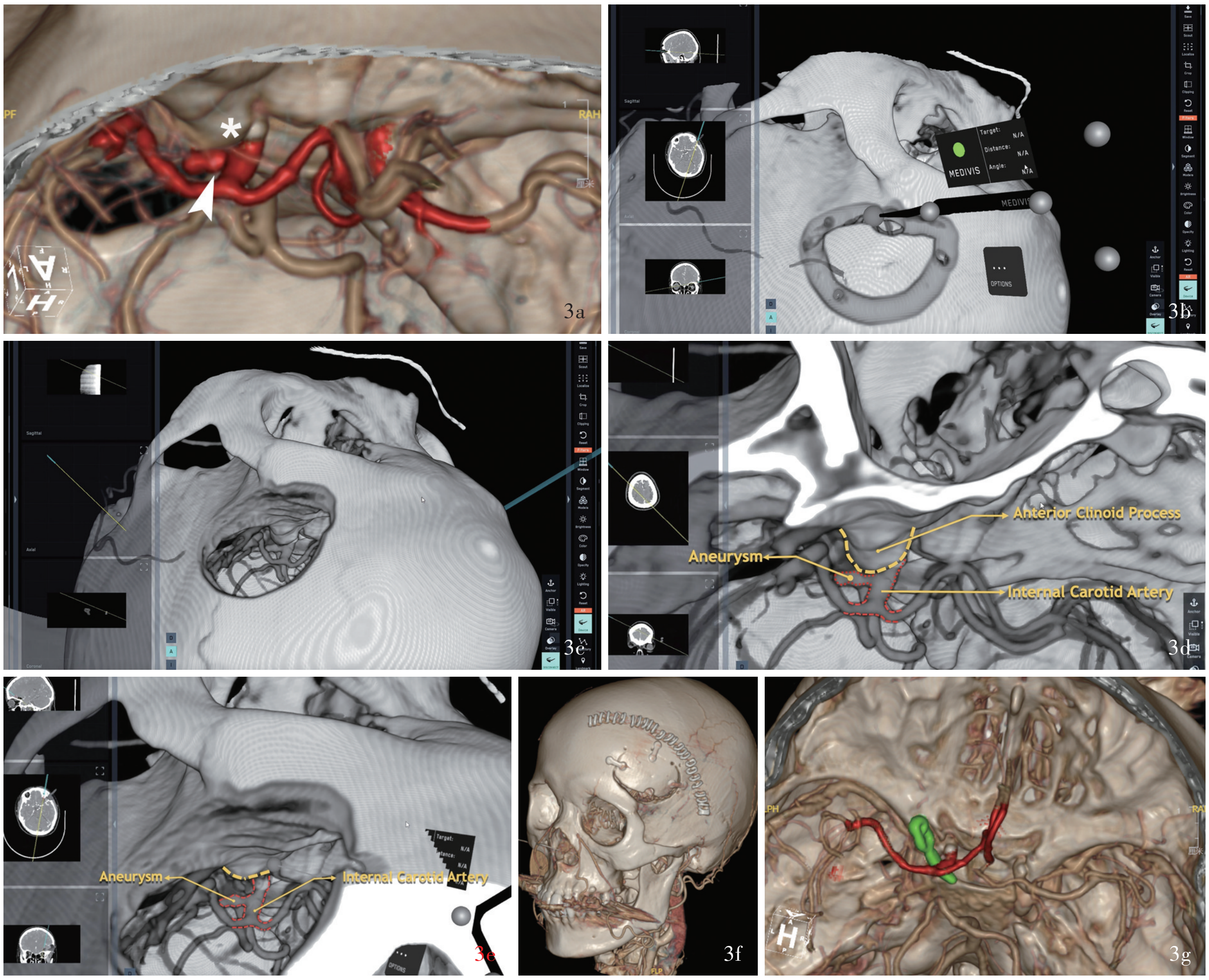

图3 颈内动脉-后交通动脉动脉瘤术前模拟与实际手术影像对比 3a 术前三维重建CTA显示颈内动脉-后交通动脉动脉瘤(箭头所示)被前床突遮挡(*所示) 3b 术前于三维重建CTA的全息影像上模拟开颅手术 3c 术前于三维重建CTA的全息影像上模拟手术体位和骨窗 3d 术前于三维重建CTA的全息影像上观察动脉瘤(红色虚线所示)与前床突(黄色虚线所示)的位置关系 3e 术前于三维重建CTA的全息影像上模拟磨除前床突(黄色虚线所示)、显露动脉瘤颈(红色虚线所示) 3f 术后三维重建CTA显示手术切口和骨瓣 3g 术后三维重建CTA显示前床突磨除、动脉瘤夹闭

Figure 3 Comparison of preoperative AR assisted internal carotid artery (ICA)-posterior communicating artery (PCoA) aneurysm clipping images with actual surgery Preoperative CTA 3D reconstruction showed the ICA-PCoA aneurysm (arrow indicates) occluded by anterior clinoid process (* indicates, Panel 3a). Preoperative simulation of craniotomy surgery via CTA 3D reconstruction (Panel 3b). Preoperative simulation of surgical position and skull via CTA 3D reconstruction (Panel 3c). CTA 3D reconstruction of aneurysm (red dotted lines indicate) and anterior clinoid process (yellow dotted lines indicate) in craniotomy simulation (Panel 3d). CTA 3D reconstruction of anterior clinoid process removal (yellow dotted lines indicate) and aneurysm neck exposure (red dotted lines indicate, Panel 3e). Postoperative CTA 3D reconstruction showed incision and bone flap (Panel 3f). Postoperative CTA 3D reconstruction showed anterior clinoid process removal and aneurysm clipping (Panel 3g).

教学中的诸多尝试[16-19],例如,基底动脉尖动脉瘤作为一种后循环动脉瘤,手术操作复杂,涉及多种手术入路,研究者一直以尸头解剖为基础,对不同手术路径进行研究和培训。近年来,虚拟现实(VR)或增强现实技术在神经外科医师培训方面显示出极大潜力,主要用于辅助神经外科医师学习基本手术操作和设计开颅手术入路[7,20],以及脑血管病的手术治疗,包括动脉瘤夹闭术和动脉瘤栓塞术[6,19,21],尤其对于青年医师,可充分培养其对神经外科手术的兴趣和信心。然而在其他颅内病变如肿瘤、神经系统变性疾病中,增强现实技术辅助神经外科医师培训的研究较少[22]。增强现实技术有助于神经外科医师快速定位病变及其毗邻的重要脑组织和骨性结构关系,尤其是复杂脑深部病变,通过术前模拟术中高风险操作,实现对重要解剖结构的深入了解。从经济学角度考虑,神经外科医师的培训需要在高年资医师的指导下不断进行手术操作学习,并在尸头上反复练习,从而耗费大量资源,而增强现

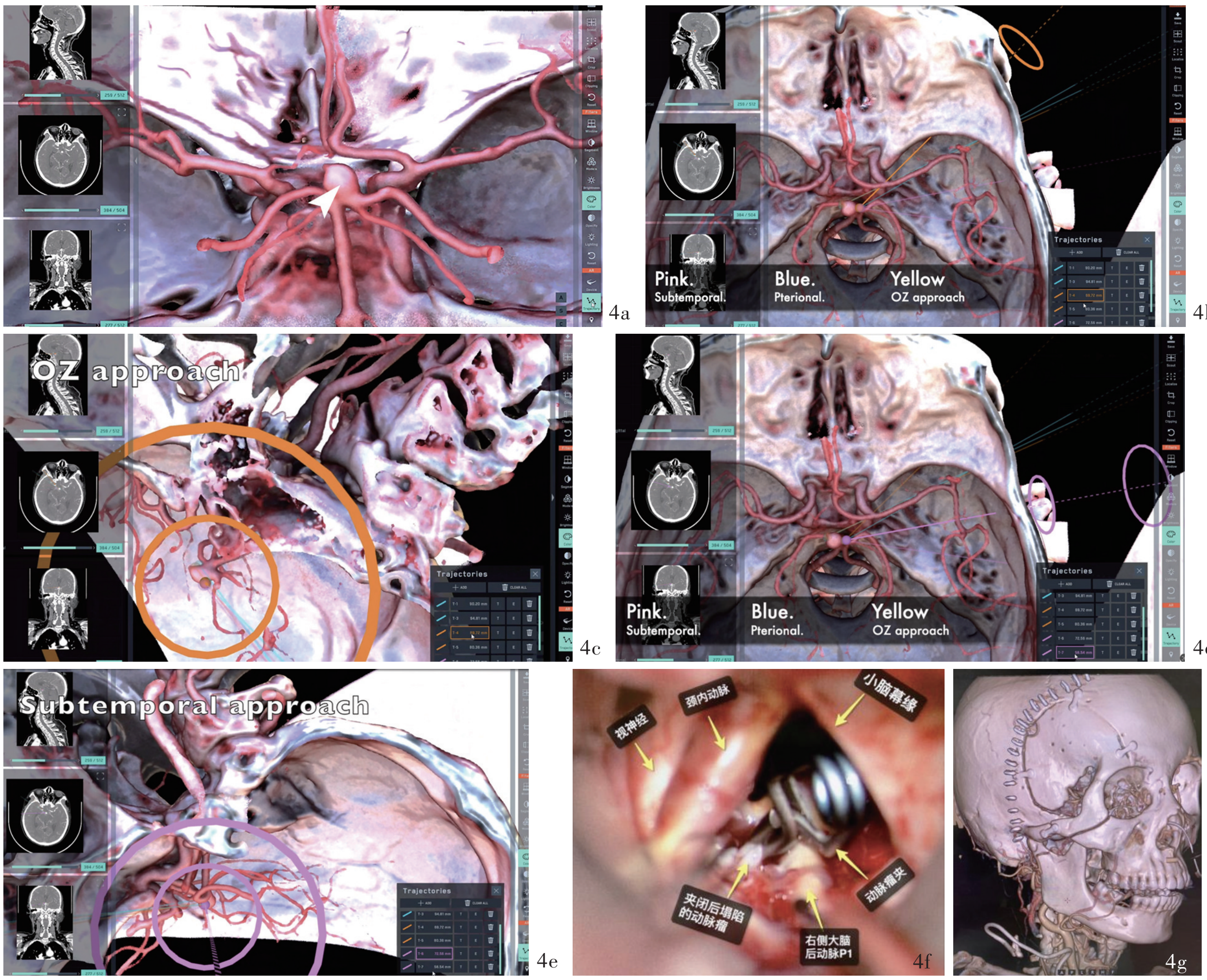

图4 基底动脉尖动脉瘤术前模拟与实际手术影像对比 4a 术前三维重建CTA显示基底动脉尖动脉瘤(箭头所示) 4b,4c 术前于三维重建CTA的全息影像上模拟经眶颧入路对动脉瘤颈的显露 4d,4e 术前于三维重建CTA的全息影像上模拟经颞下入路对动脉瘤颈的显露 4f 实际手术中采用经眶颧入路夹闭动脉瘤 4g 术后三维重建CTA显示单瓣经眶颧入路骨瓣

Figure 4 Comparison of preoperative AR assisted basilar artery apex aneurysm images with actual surgery Preoperative CTA 3D reconstruction showed basilar artery apex aneurysm (arrow indicates, Panel 4a). CTA 3D reconstruction of simulated orbito-zygomatic approach to expose aneurysm (Panel 4b, 4c). CTA 3D reconstruction of simulated subtemporal approach to expose aneurysm (Panel 4d, 4e). Intraoperative visualization of aneurysm clipping in orbito-zygomatic approach (Panel 4f). Postoperative CTA 3D reconstruction showed orbito-zugomatic of bone flap (Panel 4g).

实技术辅助神经外科医师学习手术操作也许可以显著降低医学院校的教学费用[23]。本研究所有病例的影像学资料包括CT、CTA及MRI均为临床常规扫描图像,无需特殊扫描序列,也无需影像后处理,DICOM格式数据直接导入即可,极大地缩短学习和应用时间和难度。因此,增强现实技术辅助神经外科医师培训更适用于刚刚从事或有志从事神经外科的医学生和住院医师,培养其兴趣并缓解学习过程中压力。

增强现实技术在医学领域的应用前景广阔,但在神经外科领域仍存在一些关键性技术难题。目前,增强现实技术无法准确模拟脑组织的物理性质,对于涉及脑组织操作的神经外科手术来说,是严重的限制因素。神经外科手术中的牵拉脑组织操作是极其精细且风险较高的操作步骤,外科医师需要对脑组织的触感、弹性和反应有极为精准的判断。然而,由于现有技术尚无法完全模拟脑组织的物理特性,如脑组织的非线性弹性、黏弹性及其与周围组织的相互作用等复杂特征,导致增强现实技术在术前模拟和术中指导方面的应用受到严重限制,不仅影响手术规划的精准性,而且限制神经外科医师在手术过程中通过增强现实技术获取实时

图5　模拟CCA-SA搭桥术与实际手术的影像对比　5a　术前DSA显示左锁骨下动脉闭塞并盗血（箭头所示）　5b～5d　将三维渲染的全息解剖结构投射至患者，于增强现实辅助下精准定位解剖结构　5e　于增强现实技术辅助下设计手术切口为左侧锁骨上横切口　5f　实际手术中显露左颈内动脉和左锁骨下动脉，人工血管吻合　5g　术后三维重建CTA显示桥血管通畅，盗血现象消失

Figure 5　Comparison of AR assisted CCA-SA bypass with intraoperative findings　Preoperative DSA showed left SA occlusion and presented with arterial steal syndrome (arrows indicate, Panel 5a).　AR assisted neuronavigation registration process.　Alignment of preoperative images of a patient's skull and vasculature with the patient's actual anatomy during surgery (Panel 5b-5d).　AR assisted incision design (Panel 5e).　Intraoperative visualization of ICA, SA and artificial artery bypass (Panel 5f).　Postoperative CTA 3D reconstruction showed the blood flow was vibrant and arterial steal syndrome was eliminated (Panel 5g).

指导信息的可能性。迄今尚无模拟脑组织物理性质的研究，故无法通过增强现实技术进行术前模拟和术中指导[24]。

综上所述，增强现实技术可以辅助神经外科医师进行更充分的术前规划和更精准的术中引导，还可以提供更丰富、更经济的神经外科医师培训手段，为我国培养更多的神经外科医师资源，为健康中国战略添砖加瓦。

利益冲突　无

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（收稿日期：2025-02-13）
（本文编辑：彭一帆）

《中国现代神经疾病杂志》关于谨防盗用编辑部名义的声明

近日，有作者举报不法分子盗用《中国现代神经疾病杂志》编辑部名义给作者发送邮件，以抽查往期稿件为由，甚至以“如未及时沟通导致无法抽查数据，我刊将撤下有风险的稿件”的强制性理由，要求作者必须添加其微信。这种行为严重违反了国家《关于维护互联网安全的决定》等法律法规，严重损害了我刊和作者的利益。《中国现代神经疾病杂志》特此郑重声明：我刊迄今不曾以编辑个人名义请求添加作者微信好友，编辑部人员与作者之间的联系均采用我刊公共邮箱(xdsjjbzz@263.net.cn)、公共微信和公用电话[(022)59065611，59065612]。我刊使用官网(www.xdjb.org)采编系统进行稿件处理，所有录用和缴费通知均由采编系统或公共邮箱发出，请广大作者提高安全意识，以免上当受骗。若遇假冒我刊网站、盗用编辑部名义、伪造采编中心、中介、代理等不法事件，欢迎广大作者和读者向我刊提供相关线索！对于以我刊名义从事不法活动的个别网站、邮件、个人或微信号码，我刊保留通过法律途径解决问题的权利。此声明长期有效，最终解释权归我刊所有。