MAHSA International Journal of Health and
Medicine, V4, Issue 1; September, 2024
e-ISSN: 2805-5705

Review Article **Open Access**

Advances in Minimally Invasive Surgical Treatment of Hypertensive Cerebral Haemorrhage

Changpin Liao[1#], RUSLI NORDIN[2*], Muhammad Fattah Fazel[3*], Nurul Hana Zainal Baharin3*, Jing Ye[1], Xianfu Wei[1]

[1]Department of Neurosurgery, Baise People's Hospital, Guangxi, China. [2]Faculty of Medicine, Bioscience and Nursing, MAHSA University, Kuala Lumpur, Malaysia. [3]Faculty of Pharmacy and Biomedical Sciences, MAHSA University, Kuala Lumpur, Malaysia

# These authors made equal contribution to this study.

***Corresponding Author(s):** RUSLI NORDIN (E-mail: rusli@mahsa.edu.my)

Received: 29 September 2024; Accepted: 05 October 2024; Published: 19 November 2024;

Abstract

Hypertensive cerebral haemorrhage is a significant challenge in neurosurgery due to its elevated morbidity and fatality rates. Recent advancements in minimally invasive surgical (MIS) procedures have transformed the care of this illness, yielding favourable outcomes, less patient discomfort, and expedited recovery times. This review aims to highlight current advancements in the management of hypertensive cerebral haemorrhage, emphasising minimally invasive surgery. We examine the effectiveness and safety of these therapies via a comprehensive review of recent clinical trials and meta-analyses. The review emphasises the significance of 3D slicers, neuronavigation, and robot-assisted stereotactic surgery in enhancing surgical accuracy and minimising morbidity. These approaches possess the capacity to enhance surgical outcomes. This review asserts that while minimally invasive surgical approaches for hypertensive cerebral haemorrhage are advancing swiftly, further study and development are crucial to enhance outcomes and broaden applicability.

Keywords: hypertensive cerebral haemorrhage; pathogenesis; pathophysiological changes; minimally invasive surgery； indications for surgery； timing of surgery

Introduction

Hypertensive cerebral haemorrhage (HICH) is a condition wherein elevated intracranial blood vessel pressure, due to hypertension, surpasses their capacity, leading to haemorrhage. The disease predominantly affects middle-aged and older individuals between the ages of 50 and 70 and is a prevalent cerebrovascular condition. The pathophysiology is primarily associated with inconsistent use of antihypertensive medications, resulting in significant blood pressure fluctuations, straining during defecation, emotional agitation, and other circumstances that precipitate a rapid increase in blood pressure, ultimately causing cerebral vascular rupture and haemorrhage(Hostettler et al., 2019). The disease is marked by elevated morbidity, swift start, quick progression, high death, and significant impairment rates. Historically, the care of HICH has emphasised conservative approaches, encompassing blood pressure regulation, cerebral pressure surveillance, and alleviation of symptoms. This method frequently proves inadequate in decreasing mortality and enhancing functional rehabilitation. In recent years, fast advancements in medical technology have established minimally invasive surgical treatment (MIS) as a viable alternative for the direct removal of haematomas and alleviation of brain tissue compression, while minimising injury to adjacent healthy brain tissue. Minimally invasive surgical (MIS) procedures, including stereotactic surgery, endoscopic surgery, and percutaneous transluminal aspiration, enhance surgical precision, reduce recuperation duration, and improve overall patient prognosis(Lv et al., 2023; Xu et al., 2024). Furthermore, advancements in contemporary imaging modalities, including computed tomography (CT) and magnetic resonance imaging (MRI), provide more precise diagnosis and assessment of HICH(Ai et al., 2024; Chen et al., 2023). These imaging modalities furnish essential information before surgery, including the exact position and dimensions of the haematoma, so facilitating more accurate and safer surgical procedures. Despite the considerable promise of MIS technology in addressing HICH, its effectiveness and safety require additional validation through more comprehensive clinical trials and investigations. Moreover, with the ongoing progression of technology and the formulation of novel treatment procedures, this domain is anticipated to witness further breakthroughs and enhancements in the forthcoming years. This study will examine recent advancements in minimally invasive surgical procedures for treating hypertensive cerebral haemorrhage, assessing their practical efficacy and potential avenues for further improvement.

Pathogenesis

The precise pathophysiology of hypertensive cerebral haemorrhage remains incompletely understood; however, it is well acknowledged that cerebral atherosclerosis serves as the pathological foundation for this condition. The structure of the cerebral blood arteries and their specific attributes render them more prone to hemorrhagic incidents compared to other regions of the body. The majority of the penetrating arteries at the brain's base are right-angled terminal branches of the principal stem vessels, rendering these vessels susceptible to markedly elevated luminal pressures compared to other vessels of equivalent diameter in the brain, thereby creating a region with a high incidence of hypertensive cerebral haemorrhage. The rupture of the beaded artery is the predominant cause of hypertensive cerebral haemorrhage, with ruptures of other arteries, including the thalamic penetrating artery, thalamic geniculate artery, and posterior choroid plexus artery, also occurring often. Consequently, developmental anomalies in the medial layer of the artery wall, atherosclerosis, and hypertension collectively represent the three principal risks for cerebral haemorrhage, with hypertension serving as a significant independent risk factor.

Pathophysiologic changes

The likelihood of experiencing a secondary haemorrhage or secondary active haemorrhage within 40 hours following the onset of hypertensive cerebral haemorrhage is roughly 3% among all patients with this condition. The majority of patients with cerebral haemorrhage who experienced subsequent haemorrhage had intracranial haematomas above 5.0 cm in diameter, with the mass effect intensifying as the haematoma enlarged. It is well acknowledged that secondary haemorrhage resulting from local vascular rupture, induced by peripheral tissue strain during the formation of an intracerebral haematoma, is the primary source of both early haematoma development and subsequent expansion. Haematoma enlargement predominantly happens within 6 hours of disease onset, and it is uncommon for enlargement to take place after 24 hours; thus, selecting the optimal timing for surgery is essential. Moreover, reactive cerebral oedema significantly contributes to the early decline in patients with hypertensive cerebral haemorrhage. Following a cerebral haemorrhage, blood accumulates around the haemorrhage site, resulting in structural damage to adjacent normal brain tissue and causing primary injury(Labib et al., 2017). Consequently, the blood coagulates, resulting in a pressure imbalance within the brain and establishing a pressure difference. Due to local high pressure, the nearby brain tissues experienced compression, ischaemia, displacement, oedema, and maybe necrosis. Clinical research have established that when the volume of intracerebral haematoma surpasses 150 ml within a few timeframe, intracerebral perfusion diminishes to zero, frequently resulting in patient mortality. When the volume of intracerebral haematoma is under 140 ml, the majority of patients with cerebral haemorrhage may endure the initial haemorrhage; nonetheless, the subsequent harm induced by the haemorrhage remains inevitable, leading to varying degrees of neurological impairment and, in extreme instances, potential mortality.

Present condition of therapy

Hypertensive cerebral haemorrhage encompasses both conservative internal medicine and surgical interventions. Conservative treatment involves dehydration to alleviate cranial pressure, haemostasis, nourishment of cerebral nerves, prevention and management of complications, enhancement of cerebral blood circulation, and rehabilitative exercises. During cerebral haemorrhage, the patient's brain tissue experiences not only primary injury but also secondary injury resulting from haematoma expansion, mass effect, and the toxic effects of the haematoma. When the extent of cerebral damage surpasses the reparative capacity of brain tissue and pharmacological intervention, surgical treatment becomes the subsequent diagnostic and therapeutic option. Surgical intervention can mitigate or avert the secondary damage resulting from cerebral haematoma formation, hence decreasing mortality and disability rates, preserving the patient's life, and enhancing clinical outcomes. International studies indicate that the efficacy of surgical intervention surpasses that of conservative medicinal treatment, a consensus supported by the majority of professionals and scholars. The primary advantages of surgical intervention include the swift removal of intracerebral haematoma, effective haemorrhage control, alleviation of pressure on brain tissue, expedited patient recovery, and enhancement of clinical prognosis. Nevertheless, conventional craniotomy techniques often yield suboptimal results owing to elevated surgical risks and postoperative problems. Nonetheless, the progression of medical technology has rendered minimally invasive surgery (MIS) a novel solution to this complex issue.

Minimally invasive surgical interventions

In recent years, minimally invasive drilling drainage has gained increasing popularity owing to its advantages of reduced invasiveness, simplicity, ease, and notable efficacy(Chi et al., 2014; Lian et al., 2024). In 1978, Backlund initially suggested the minimally invasive insertion of tubes and drainage of intracranial haematomas for the management of hypertensive cerebral haemorrhage(Backlund & von Holst, 1978). For patients with hypertensive cerebral haemorrhage who are ineligible for open haematoma removal surgery, such as elderly individuals or those with significant organ dysfunction, the implantation and drainage of a haematoma puncture tube is a more suitable option. MISTIE III, a phase III randomised open clinical case-control trial with 500 participants, examined the efficacy of minimally invasive surgery combined with rt-PA for treating intracranial bleeding, establishing that minimally invasive surgery is an exceptionally successful intervention for cerebral haemorrhage(Hanley et al., 2019). Twelve high-quality randomised controlled trials involving 1,955 patients conducted by ZHOU et al. demonstrated that minimally invasive treatment of spontaneous supratentorial cerebral haemorrhage may be more advantageous than alternative methods for hypertensive cerebral haemorrhage(X. et al., 2012). Numerous comparative investigations by Scaggiante et al. have corroborated that individuals with supratentorial cerebral haemorrhage may derive greater advantages from minimally invasive treatment(Jacopo et al., 2018). Minimally invasive puncture and drainage is increasingly utilised in clinical settings due to its surgical simplicity, reduced operative duration, minimal trauma, and definitive efficacy, which mitigates postoperative stress responses and effectively prevents complications. Surgery is the sole option for haematoma removal. Mckissock's study determined that minimally invasive treatment for cerebral haemorrhage is considerably more successful than conservative approaches, potentially enhancing patient survival and outcomes(Gregson et al., 2013; Hemphill et al., 2015). This indicates that minimally invasive treatment is, in certain respects, preferable to conservative treatment. Currently, soft-channel puncture and tube placement are extensively utilised in clinical practice due to their minimal invasiveness, high biocompatibility, cost-effectiveness, ease of adjustment, and resistance to obstruction. Enhancing the precision of puncture positioning has emerged as a critical factor in minimally invasive access surgery. In clinical practice, precise positioning is essential for the surgical management of cerebral haemorrhage, significantly impacting the assessment of therapeutic efficacy and the enhancement of prognosis. Presently, the minimally invasive surgical techniques employed in clinical practice mostly consist of: conventional minimally invasive drilling and drainage, stereotactic minimally invasive drilling and drainage facilitated by 3D slicer software, neuronavigation, and neurosurgery robotics.

Traditional minimally invasive drilling and drainage

In recent years, the ongoing advancement of imaging technology has led to the widespread application of classic drilling and drainage surgery, in conjunction with urokinase (UK) or recombinant tissue-type plasminogen activator (rt-PA), for the treatment of patients with hypertensive cerebral haemorrhage(Huang et al., 2023; Xiong et al., 2024). Traditional stereotactic surgery is executed via minimally invasive drilling drainage with a soft channel. This technique employs an adapted stereotactic approach to ascertain the highest point of the haematoma and the puncture target through preoperative CT localisation and a specialised localisation ruler, facilitating the selection of a suitable puncture trajectory and enabling directional drilling with specialised instruments, including cone-cranial apparatus. A drainage tube is placed into the haematoma cavity to aspirate the haematoma, and urokinase lysate is administered postoperatively to liquefy and facilitate drainage of the haematoma. This approach is appropriate for patients exhibiting modest haematoma volume, a relatively mild illness, a low level of unconsciousness, a prolonged onset duration, an absence of precursor symptoms of brain herniation, and is particularly advantageous for elderly and frail individuals. The puncture tube is a pliable conduit, and during the puncture procedure, the drainage tube functions to separate brain tissue and nerves rather than incising, so minimising damage. It is less susceptible to artefacts during postoperative evaluation, hence enhancing postoperative CT assessment. In certain aspects, pain-invasive drilling and draining has demonstrated superiority over conservative treatment or craniotomy, particularly in emergency scenarios where the surgery can be executed at the bedside under local anaesthesia. Conversely, drilling via a flexible catheter mitigates mechanical harm and is especially recommended for moderate cerebral haemorrhage situations(Broderick, 2007). Nonetheless, there are certain constraints associated with drilling and drainage surgery: (1) Unarmed minimally invasive drilling and drainage surgery frequently depends on the clinician's expertise, resulting in suboptimal puncture accuracy, which can cause improper tube placement, often at the periphery of the haematoma cavity or at an unsuitable depth, thereby hindering haematoma evacuation and resulting in inadequate drainage; (2) The haemostatic procedure is not directly observable, and the puncture technique may injure blood vessels, potentially causing rebleeding within the haematoma cavity. Secondly, the decompression efficacy of this surgery is constrained, and the inadequate intraoperative haematoma evacuation necessitates numerous postoperative urokinase injections to liquefy and drain the haematoma, hence elevating the risk of iatrogenic cerebral infection. The inadequate clearance of haematoma can result in residual haematoma, which may generate neurotoxins and inflict secondary harm on brain tissue. Repeated piercing can readily induce rebleeding of the haematoma cavity. The puncture method often traverses the lateral temporal approach, necessitating passage via the posterolateral fissure, which may result in vascular injury to the fissure, subsequently causing rebleeding and exacerbating the patient's condition. Consequently, enhancing the precision and safety of this surgical technique has emerged as the objective of ongoing research(Fam et al., 2017; Liu et al., 2017). Furthermore, drilling drainage surgery typically requires a delay of 12-24 hours post-bleeding to allow for haematoma stabilisation, rendering it unsuitable for patients experiencing unstable bleeding or brain herniation in the acute phase of cerebral haemorrhage. Ultimately, drilling and drainage surgery is conducted manually, which impairs the precision of direction and depth during puncture, leading to the drainage tube's inability to correctly access the primary target of the haematoma cavity, so compromising the efficacy of haematoma drainage(Gebel & Broderick, 2000; Wang et al., 2015).

Stereotactic surgery

Stereotactic surgery involves employing the notion of stereotactic positioning to ascertain the spatial coordinates of target sites within the skull through a specific methodology(Tang et al., 2023; Xie et al., 2024). The spatial coordinates are computed and transformed into coordinates defined within the instrument's three-dimensional space. They are subsequently directed to the target site within the skull via a specific equipment or device to appropriately address the anatomical structure or lesion at that place. The specific device that executes this approach is referred to as a brain stereotactic apparatus. The accurate execution of this procedure necessitates several fundamental techniques, each possessing a unique method of implementation and a means of integrating the various techniques, culminating in the creation of specialised brain stereotactic devices. Presently, stereotactic surgery in prevalent clinical practice typically depends on supplementary tools such as neuronavigation, neurosurgical robots, and 3D slicer software. These approaches exhibit great accuracy; nevertheless, the initial two auxiliary devices are costly, unwieldy, and challenging to operate, coupled with prolonged preoperative preparation time, hence restricting their promotion and application in most grassroots hospitals. As computer technology advances, clinicians' need for data analysis has evolved beyond mere observation of results to include participatory processing of outcomes. Currently, professional software is advancing swiftly in the technology of processing pictures obtained from medical imaging devices, and is progressively becoming popular in clinical practice, successfully assisting clinicians in precise diagnosis and localisation.

3D slicer Software Assisted Stereotactic Surgery

Presently, 3D slicer software is extensively utilised in clinical practice as an image processing instrument to aid in surgical positioning and represents the most economical choice.3D Slicer is a complimentary and open-source software with no financial expenditure required(Xu et al., 2014; Zhao et al., 2023). The software is a 3D visualisation medical image processing platform collaboratively developed in 1998 by the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology (MIT) and the Surgical Planning Laboratory at Brigham and Women's Hospital in Boston, USA. In China, Professor Chen Xiaolei of the PLA General Hospital was the inaugural individual to implement and advocate for the program(Hou et al., 2016). Users may obtain the software from http://download.slicer.org, with annual downloads exceeding 75,000(Norton et al., 2017). 3D slicer software employs soft-channel technology to facilitate the positioning of minimally invasive drilling and drainage, offering ease of operation and suitability for marketing and application in primary healthcare facilities.

In the initial stages, surgeons utilised 3D slicer software to project haematomas onto the patient's body surface and capture screenshots. Subsequently, augmented reality (AR) was integrated by modifying the image's transparency and employing the Sina software for Android devices or system tools for Apple devices. Augmented Reality overlays computer-generated virtual items onto real-world environments via a display device, with software or applications managing visual algorithms and graphic rendering, ultimately projecting the outcome onto a monitor or mobile device screen. This technique can be aligned with the patient's head to ascertain the position of the haematoma. Nonetheless, this strategy presents certain issues:The disparity in lens focal length may result in scaling and distortion; thus, it is essential to maintain the magnification ratio of the image in the 3D slicer screenshot consistent with that of the mobile phone's focal length, however the precise calculation method remains ambiguous. This method cannot be accurately classified as augmented reality technology and is solely relevant to front-side or front-top scenarios. During CT scanning and placement, the patient's head orientation and the angle of virtual image interception must adhere to specific criteria. To address the aforementioned issues, a mobile application named 'PTV 3D' was introduced in 2019, which creates a model import code by exporting the model in OBJ format from 3D Slicer and thereafter uploading it to PTV's case library. Users may launch the 3D software on their mobile devices, choose the standard version, and input the code to obtain a 360-degree perspective of the 3D reconstructed image, with the ability to zoom in and out, as well as modify the colour and transparency of the image. Furthermore, the software enhances positioning by utilising body positioning indicators, significantly augmenting efficiency and precision. The 3D slicer program presently possesses the ability to integrate CT, MRI, DSA, and diffusion tensor imaging (DTI) data, enabling the three-dimensional reconstruction of anatomical structures including sulci, gyri, ventricles, nerves, intracranial arteries, and white matter fibres(Bruns, 2019). The program has been utilised in various domains of neurosurgery, including brain tumours, trigeminal neuralgia, facial spasms, cerebrovascular disease, and epilepsy(Han et al., 2016; Yao et al., 2018).

The 3D slicer is a validated and dependable approach for haematoma localisation, aiding in the identification of deep cerebral haematomas and offering more precise informational parameters. Utilising 3D Slicer image processing software alongside the patient's preoperative head CT imaging data, effective 3D modelling of intracranial haematomas and the skull can be accomplished. The software interface allows for the visualisation of the haematoma's precise location by rotating the 3D model, enabling its localisation to the patient's skull in conjunction with the appropriate Kronlein body placement technique. Minimally invasive puncture and drainage of the cerebral haematoma can be executed with the aid of 3D slicer software for accurate positioning. Utilising the patient's preoperative CT, one can achieve 3D modelling of the intracranial haematoma and skull to accurately assess the hematoma's precise location and to devise a simulated puncture trajectory along the long axis to determine the puncture site, angle, and depth of the channel. Furthermore, the haematoma clearance rate post-surgery may be precisely calculated.

3D slicer software offers an efficient, time-saving, and precise positioning tool for minimally invasive drilling and draining procedures. The 3D slicer markedly outperforms the conventional technique of identifying intracranial haematomas solely through CT films, facilitating more effective and precise puncture of these haematomas. This advancement enhances the rate of early haematoma removal and alleviates brain tissue compression promptly, thereby improving prognosis. The superiority of 3D slicers is primarily seen in the following aspects: (1) Cost-effective: The 3D slicer offers comparable functionalities and is entirely free, in contrast to other commercial applications. (2) Compatibility: The 3D slicer is operable on 64-bit Linux, MacOSX, and Windows operating systems, and it accommodates numerous standard medical image file formats (Fedorov et al., 2012). The source code of the 3D slicer program is entirely open, and the algorithms are publicly accessible, allowing users to incorporate other algorithms and application modules for functional enhancement as required. (3) Practicality: A 3D slicer can integrate nearly all imaging data for simulation and 3D reconstruction, while also offering quantitative characteristics such as distance, area, and volume, applicable for 3D printing, condition delivery, surgical planning, and previewing. (4) Nonetheless, 3D slicer possesses specific limitations: placement accuracy is influenced: while 3D slicer-assisted placement is more precise than anatomical positioning, variations in lesion sizes and depths may result in mistakes in body surface projection. Moreover, the evaluation of matching in augmented reality is solely reliant on visual observation, resulting in a deficiency of precise input.Eftekhar et al. investigated the localisation precision of the 3D Slicer software in their research.The 3D slicer was utilised alongside the sina program to identify lesions less than 3 cm in 11 patients, and the localisation deviation was assessed using a neuronavigation system. The results indicated that the discrepancy between the lesion centre identified by sina and that identified by the neuronavigation system was 10.2 ± 2 mm(Eftekhar, 2016). Chen et al. employed a comparable methodology, achieving a localisation error of 4.4 ± 1.1 mm(Chen et al., 2017). Conversely, Guo et al. demonstrated an inaccuracy of up to 13.6 ± 0.55 mm.(Yu et al., 2019). (5) The data from the 3D slicer software primarily originate from preoperative imaging and do not offer real-time positioning information during operation. (6) Infratentorial lesions exhibit reliable localisation via 3D slicer; however, the anatomy of the posterior cranial fossa differs from that of supratentorial structures. For instance, the cerebellar lobes are challenging to identify for reconstruction, and the small diameter of the cortical veins in the posterior cranial fossa complicates 3D reconstruction efforts. (7) The program is now available just in English, and while the reconstruction of haematomas is straightforward and easy to comprehend, conducting more comprehensive investigations, such as formulating preoperative planning and reconstructing white matter filaments, would pose challenges.

Stereotactic surgery supported by neuronavigation

In recent years, neuronavigation techniques have gained prevalence in neurosurgery practice(Xie et al., 2024). This technology amalgamates neuroimaging, stereotactic technology, and microsurgical techniques to attain accurate three-dimensional localisation of intracerebral lesions and real-time target tracking via a computer system. This approach, when used to neuronavigated stereotactic surgery for hypertensive cerebral haemorrhage, markedly diminishes surgical trauma and consequences(Haseeb et al., 2024; Zhang et al., 2024). The 'registration' process during surgery is essential for ensuring high-precision navigation. Presently, prevalent registration methodologies encompass real-time structured light navigation and electromagnetic navigation. Real-time structured light navigation employs an automated two-step registration technique utilising the frontal-orbital-facial head contour as a stable reference point, distinguished by its high precision, absence of preoperative marking, and operational simplicity. Conversely, electromagnetic navigation necessitates an additional operative CT scan and complex marker-based registration, hence extending the duration of the procedure. Real-time structured light navigation necessitates simply the intraoperative utilisation of markerless image data, significantly decreasing registration duration and conserving surgical time. Moreover, additional benefits of this strategy encompass (1) Minimally invasive and less stressful surgical procedures. (2) The capability to identify and precisely execute puncture and draining procedures in real time. (3) The utilisation of the patient's preoperative CT data for three-dimensional reconstruction and computer-assisted design efficiently circumvents vital blood vessels and functional areas. (4) Marker-less registration decreases surgery duration and expenses, while decreasing exposure to X-ray radiation. (5) The navigation device utilises structured light scanning, eliminating the requirement for contact with the surgical site and so minimising the risk of infection. These attributes render neuronavigation-assisted stereotactic surgery a significant technical alternative for the management of hypertensive cerebral haemorrhage.

In neuronavigation-assisted stereotactic surgery for the treatment of hypertensive cerebral haemorrhage, the residual haematoma is lysed intraoperatively by extracting a portion of the haematoma and injecting it with urokinase in the postoperative period. Although the neuronavigation system itself does not directly remove the haematoma, its key advantage is the highly accurate virtual visualisation of the haematoma location and puncture dynamics via a navigation stick that displays the haematoma location and puncture dynamics in real time on the screen. This optimises the puncture procedure and enables the surgeon to adjust the puncture needle in real time to perform multi-point puncture suction and effectively remove the majority of the haematoma. This technique dramatically increases the volume and precision of suction and reduces the risk of damage to surrounding tissues compared to traditional surgery. In addition, the neuronavigation system can accurately adjust the depth and position of the puncture needle to achieve intermittent multipoint aspiration of fragmented haematoma, which significantly increases the intraoperative haematoma removal rate and thus reduces the retention time of the postoperative drainage tube. The judicious selection of the puncture route is especially appropriate for addressing prevalent regions of hypertensive cerebral haemorrhage, such as the basal ganglia. In these regions, the majority of haematomas have a 'kidney-shaped' morphology with a significant aspect ratio; hence, selecting a frontal puncture pathway can optimise haematoma evacuation and mitigate the risk of vascular damage. Neuronavigation devices have shown considerable benefits in directing accurate puncture and haematoma extraction in deeply situated haematomas, such as those in the thalamus or midbrain, while minimising injury(Krylov et al., 2008; Miao et al., 2012; Yan et al., 2015). Additional benefits of neuronavigation-assisted surgery encompass (1) The navigation workstation can precisely identify the optimal puncture site to circumvent critical functional regions and vascular concentrations, significantly minimising brain tissue damage and ensuring direct targeting of the haematoma's centre, thereby effectively preventing the additional harm linked to blind punctures that may occur with traditional CT localisation. (2) Accurate puncture site guidance leads to an elevated incidence of haematoma evacuation, diminishes the recurrence of haemorrhage, and mitigates neurological impairment. Consequently, neuronavigation-assisted stereotactic surgery has emerged as a pivotal method in the management of hypertensive cerebral haemorrhage, with the anticipation of significantly enhancing surgical outcomes and therapeutic efficacy in the future.

Neurosurgical Surgery Robot-Assisted Stereotactic Surgery

Neurosurgical robot-assisted stereotactic surgery is categorised as frameless stereotactic surgery, distinguished by its rapid and less invasive procedure(Wu et al., 2021; Zou et al., 2024). In cases of cerebral bleeding, CT scanning can be conducted by affixing metal markers to the skull, eliminating the necessity for intricate head frame stabilisation, hence considerably reducing the duration of the preoperative localisation assessment. Upon completion of the CT scan, the image data can be instantly integrated into the robotic-less surgical system, which will then devise the puncture trajectory and execute the surgical procedure. Consequently, the interval from examination to puncture is generally approximately 20 minutes. Conversely, framed stereotactic surgery necessitates head frame fixation; nonetheless, it is more time-consuming since certain patients with brain bleeding may be too unconscious to cooperate adequately and require assessment on specialised CT or MRI equipment. In cases of cerebral haemorrhage, timely intervention is critical, and frameless stereotactic robotic surgery provides an opportunity to gain crucial time for life-saving measures. Moreover, frameless stereotactic robotic surgery is concise and less invasive, making it appropriate for patients with compromised health and concomitant multi-organ injuries, hence broadening the surgical indications relative to open haematoma evacuation. The procedure eliminates the necessity for a head frame utilised in conventional stereotactic surgery, so diminishing patient discomfort, mitigating the elevation of blood pressure associated with pain, and consequently lowering the chance of haematoma cavity expansion due to increased blood pressure. The frameless stereotactic robotic surgical procedure exhibits a high level of automation and precise placement, hence diminishing the technical demands on the surgical operator and facilitating clinical adoption. Numerous investigations have validated that neurosurgical robotic-assisted stereotactic haematoma aspiration for hypertensive cerebral haemorrhage has a favourable prognosis in clinical practice(Chen et al., 2011; UMEBAYASHI et al., 2010).

Additionally, the subsequent conditions must be acknowledged during the surgical procedure: (1) Four Metal markers should be affixed at the root of the snout, 3-5 cm above it, and at the apex of the auricle on both sides. (2) The surgical trajectory should circumvent the functional area, selecting a site where the basal ganglia is approximately aligned with the frontal pole to prevent injury to the brain's functional regions or the formation of new haematomas. For haematomas located near the subcortex or irregularly shaped and distant from the frontal region, the most direct approach to the haematoma that circumvents critical functional areas should be selected for puncture, with the target point typically positioned 1.0 to 1.5 cm posterior to the centre of the haematoma. (3) Regarding patient positioning, if the angle of the robotic arm approaches 90° or 180°, the puncture channel becomes inaccessible; thus, the patient should be repositioned to a lateral recumbent position to guarantee the puncture surface is orientated upwards. (4) Contouring pillows are typically utilised for awake patients, whereas agitated individuals should undergo the treatment under general anaesthesia to achieve precise haematoma identification and to prevent head movement. (5) Intraoperative monitoring of the patient's breathing, blood pressure, consciousness, and pupillary alterations must be conducted. Following the perforation of the skull, the dura mater must be penetrated with a sharp puncture needle, after which the dural opening should be expanded with a blunt puncture needle to avert the risk of an epidural haematoma. The aspiration of the haematoma should be performed gently and slowly. In the event of fresh bleeding, saline may be used for flushing, and thrombin should be given to halt the haemorrhage. A drain should be inserted and closed, followed by a further cranial CT scan for monitoring.6 In cases of haematomas that have infiltrated the ventricles, external lateral ventricular drainage is typically employed as a standard procedure. A cranial CT scan should be conducted 24 hours post-surgery to assess the residual volume of the haematoma. If the haematoma volume is below 5 ml, the tube may be removed; if the haematoma volume exceeds 5 ml, urokinase should be administered routinely to facilitate haematoma dissolution and drainage until the haematoma is substantially resolved.

In conclusion, robotic-assisted stereotactic surgery for neurosurgery is an innovative technology that has significantly advanced the surgical management of hypertensive cerebral haemorrhage. This technology integrates robots with stereotactic navigation systems, presenting numerous potential benefits and advancements in neurosurgery. In the future, we anticipate the advancement of this approach to provide patients safer, more precise, and more successful neurosurgical interventions.

Indications for surgery and time selection in hypertensive intracerebral haemorrhage

Indications for surgical intervention

During surgical intervention for patients with cerebral haemorrhage, it is imperative to evaluate factors such as preoperative haemorrhage volume, location of the bleeding, time of start, level of consciousness, and associated comorbidities. For patients with minimal bleeding, mild neurological impairment, and intact consciousness, conservative internal treatment may be employed to mitigate potential surgical complications that could adversely impact neurological recovery. For patients with a haematoma volume of up to 30 ml supratentorial or 10 ml infratentorial, who present with aphasia, hemiparesis, and minor consciousness impairment, internal conservative management should be prioritised, with surgical intervention readiness maintained at all times. Cranial CT evaluation is necessary during treatment to assess any increase in haematoma volume or deterioration of consciousness; if such trends are observed, prompt surgical intervention is warranted. In patients with substantial haematoma volume, irregular respiration, dilated pupils, and profound coma, either internal conservative management or surgical intervention may be more beneficial; however, the prognosis remains unfavourable, and surgical intervention is not indicated for these individuals. The criteria for surgical intervention encompass: (1) The patient is under 70 years of age; the volume of supratentorial haematoma exceeds 30 ml, and the volume of infratentorial haematoma exceeds 10 ml. (2) The effect of the haematoma is exacerbated. (3) A discernible midline displacement is present; the situation deteriorates steadily despite medical intervention. (4) The state of awareness is between coma and mild coma. (5) The GCS score attains 6 points or greater.

Timing of surgery

The main goal of treating cerebral haematoma with surgery is to remove the haematoma in order to reduce the intracranial pressure, so that the compressed neurons can be restored, and to prevent a series of pathophysiological changes caused by the bleeding and to change the state of vicious circle. Most deaths in patients with hypertensive cerebral haemorrhage occur within 24 hours of the onset of the disease, while approximately 72.8% to 92.5% of patients die within the first week of the disease(Zhang et al., 2012).It is currently believed that early surgical treatment within 12 hours of the onset of hypertensive cerebral haemorrhage is beneficial to the patient's prognosis. Although ultra-early (<6h) surgical treatment can promptly remove the haematoma and reduce its compression on brain tissue and nerves, patients are more likely to develop secondary haemorrhage(Zhou et al., 2011).Studies have shown that for minimally invasive removal of intracranial haematomas 8-24 h after cerebral haemorrhage, satisfactory results can be obtained in terms of complete clearance rate and neurological function recovery(Zhu et al., 2010). Nevertheless, it has been observed that premature surgery should be eschewed due to the potential for haematoma expansion, which may result in postoperative re-bleeding, so rendering delayed surgery safer.(Kellner et al., 2018). The scientists determined that the ideal timeframe for surgical intervention of cerebral haematomas is from 6 to 24 hours post-onset. Performing surgery within this timeframe diminishes the likelihood of subsequent haemorrhage and leads to favourable neurological recovery and prognosis for the patient's brain post-operation.

Future Directions

Despite ongoing controversies in current clinical studies regarding the efficacy of minimally invasive surgery for hypertensive cerebral haemorrhage, and the absence of high-quality, large-scale trials demonstrating its capacity to enhance functional outcomes or markedly decrease mortality rates, minimally invasive surgery is progressively emerging as a significant trend in surgical treatment within this domain. We are unequivocally in favour of the future advancement of minimally invasive surgery.

Published randomised controlled trials, like the MISTIE trial, yielded disappointing outcomes, highlighting the limitations of minimally invasive surgery in certain instances. Consequently, we assert that next clinical investigations ought to prioritise the quality of trial design and enhance the standardisation of trials to guarantee the reliability and validity of outcomes. Simultaneously, researchers ought to investigate various procedures and methodologies of minimally invasive surgery comprehensively, aiming to identify more appropriate treatment alternatives for patients.

The advancement of minimally invasive surgical techniques and neuroimaging renders the enhancement and optimisation of surgical procedures particularly crucial. Advanced imaging techniques enable more precise localisation of haematomas, consequently diminishing surgical risks and enhancing treatment outcomes. Our team is presently engaged in the promotion of a research and development initiative focused on an intelligent and precise minimally invasive system for the removal of haematomas associated with cerebral haemorrhage. This project aims to facilitate the timely adjustment of puncture needle positioning, judiciously guide the administration of liquefying agents, and enable real-time monitoring of dynamic haematoma drainage fluid and intracranial pressure fluctuations through a noninvasive and precise haematoma localisation system coupled with a dual-channel puncture needle system.

Furthermore, we intend to create a cloud-based database to leverage substantial data for enhancing clinical decision-making. This system will furnish surgeons with real-time data assistance to facilitate more empirical decision-making during surgery. By integrating these technologies, we aim to enhance safety and efficacy in minimally invasive surgery.

We are confident that ongoing clinical studies of innovative minimally invasive surgical methods, along with the persistent advancement and innovation in these procedures, will enhance the future of minimally invasive therapy for hypertensive cerebral haemorrhage. Future research should concentrate on enhancing not only the surgical technique but also the comprehensive management of the patient, encompassing postoperative rehabilitation and follow-up care. Considering these criteria, we anticipate improved outcomes in the implementation of minimally invasive surgery and the provision of more effective treatment choices for patients with hypertensive cerebral haemorrhage.

Summary

Minimally invasive surgery for hypertensive cerebral haemorrhage has advanced significantly in recent years. Previous research indicate that early minimally invasive surgical excision of cerebral haematoma can markedly enhance the complete clearance rate and return of neurological function in patients. Nevertheless, meticulous selection of surgical timing and technique is essential to prevent ultra-early surgery, hence minimising the danger of postoperative haematoma expansion. Typically, surgery is optimally performed 6 to 24 hours following a brain haemorrhage. These findings offer definitive guidelines for the minimally invasive surgical management of hypertensive cerebral haemorrhage, enhancing patient safety and therapeutic outcomes. Nevertheless, additional research is required to investigate more accurate surgical scheduling and techniques to improve treatment outcomes. In conclusion, advancements in minimally invasive surgical techniques for hypertensive cerebral haemorrhage have yielded improved treatment options for patients; nevertheless, further research and refinement are necessary to further optimise treatment outcomes.

Acknowledgements

Authors' Contributions: Conceptualization, X.F.W., J.Y.; Methodology, R.N.; Software, N.H.Z.B; Data Curation, M.F.F.; Writing - Original Draft Preparation, C.P.L.; Writing - Review and Editing, C.P.L., R.N. All authors have read and agreed to the published version of the manuscript.

Funding: Guangxi Zhuang Autonomous Region Health and Family Planning Commission (Z-L20241761).

Competing Interests: The authors declare no competing interests.

References:

Ai, M., Zhang, H., Feng, J., Chen, H., Liu, D., Li, C., Yu, F., & Li, C. (2024). Research advances in predicting the expansion of hypertensive intracerebral hemorrhage based on CT images: an overview [Journal Article; Review]. *Peerj*, 12, e17556. http://doi.org/10.7717/peerj.17556

Backlund, E. O., & von Holst, H. (1978). Controlled subtotal evacuation of intracerebral haematomas by stereotactic technique [Journal Article]. *Surg Neurol*, 9(2), 99-101.

Broderick, J. (2007). Guidelines for the management of spontaneous intracerebral hemorrhage in adults: 2007 update: a guideline from the American Heart Association/American Stroke Association Stroke Council, High Blood Pressure Research Council, and the Quality of Care and Outcomes in Research Interdisciplinary Working Group. *Stroke*, 38

Bruns, N. (2019). 3D Slicer [Journal Article]. *Der Unfallchirurg*, 122(8), 662-663. http://doi.org/10.1007/s00113-019-0654-4

Chen, J. G., Han, K. W., Zhang, D. F., Li, Z. X., Li, Y. M., & Hou, L. J. (2017). Presurgical Planning for Supratentorial Lesions with Free Slicer Software and Sina App. *World Neurosurgery*, 106, 193-197.

Chen, X., Chen, W., Ma, A., Wu, X., Zheng, J., Yu, X., Wang, Y. J., & Wang, D. (2011). Frameless stereotactic aspiration and subsequent fibrinolytic therapy for the treatment of spontaneous intracerebral haemorrhage [Evaluation Study; Journal Article]. *British Journal of Neurosurgery*, 25(3), 369-375. http://doi.org/10.3109/02688697.2010.520765

Chen, Z. Z., Salvador, Á. E., Hilario, B. A., Cárdenas, D. C. A., Romero, C. J., & Ramos, G. A. (2023). Primary and secondary non-traumatic intra-cerebral haemorrhage: MRI findings [Journal Article; Review]. *Radiologia (Engl Ed)*, 65(2), 149-164. http://doi.org/10.1016/j.rxeng.2023.01.003

Chi, F. L., Lang, T. C., Sun, S. J., Tang, X. J., Xu, S. Y., Zheng, H. B., & Zhao, H. S. (2014). Relationship between different surgical methods, hemorrhage position, hemorrhage volume, surgical timing, and treatment outcome of hypertensive intracerebral hemorrhage [Journal Article]. *World Journal of Emergency Medicine*, 5(3), 203-208. http://doi.org/10.5847/wjem.j.issn.1920-8642.2014.03.008

Eftekhar, B. (2016). A Smartphone App to Assist Scalp Localization of Superficial Supratentorial Lesions—Technical Note [Journal Article; Technical Report]. *World Neurosurgery*, 85, 359-363. http://doi.org/10.1016/j.wneu.2015.09.091

Fam, M. D., Hanley, D., Stadnik, A., Zeineddine, H. A., Girard, R., Jesselson, M., Cao, Y., Money, L., McBee, N., Bistran-Hall, A. J., Mould, W. A., Lane, K., Camarata, P. J., Zuccarello, M., & Awad, I. A. (2017). Surgical Performance in Minimally Invasive Surgery Plus Recombinant Tissue Plasminogen Activator for Intracerebral Hemorrhage Evacuation Phase III Clinical Trial [Clinical Trial, Phase III; Journal Article; Randomized Controlled Trial]. *Neurosurgery*, 81(5), 860-866. http://doi.org/10.1093/neuros/nyx123

Fedorov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J. C., Pujol, S., Bauer, C., Jennings, D., Fennessy, F., & Sonka, M. (2012). 3D Slicer as an image computing platform for the Quantitative Imaging Network. *Magnetic Resonance Imaging*, 30(9), 1323-1341.

Gebel, J. M., & Broderick, J. P. (2000). Intracerebral hemorrhage. *Neurologic Clinics*, 18(2), 419-438.

Gregson, B. A., Rowan, E. N., & Mendelow, A. D. (2013). Letter to the editor by Gregson et al regarding article, "minimally invasive surgery for spontaneous supratentorial intracerebral hemorrhage: a meta-analysis of randomized controlled trials" [Comment; Letter]. *Stroke*, 44(5), e45. http://doi.org/10.1161/STROKEAHA.111.000296

Han, K. W., Zhang, D. F., Chen, J. G., & Hou, L. J. (2016). Presurgical visualization of the neurovascular relationship in trigeminal neuralgia with 3D modeling using free Slicer software [Evaluation Study; Journal Article]. *Acta Neurochirurgica*, 158(11), 2195-2201. http://doi.org/10.1007/s00701-016-2936-8

Hanley, D. F., Thompson, R. E., Rosenblum, M., Yenokyan, G., Lane, K., McBee, N., Mayo, S. W., Bistran-Hall, A. J., Gandhi, D., Mould, W. A., Ullman, N., Ali, H., Carhuapoma, J. R., Kase, C. S., Lees, K. R., Dawson, J., Wilson, A., Betz, J. F., Sugar, E. A., Hao, Y., Avadhani, R., Caron, J. L., Harrigan, M. R., Carlson, A. P., Bulters, D., LeDoux, D., Huang, J., Cobb, C., Gupta, G., Kitagawa, R., Chicoine, M. R., Patel, H., Dodd, R., Camarata, P. J., Wolfe, S., Stadnik, A., Money, P. L., Mitchell, P., Sarabia, R., Harnof, S., Barzo, P., Unterberg, A., Teitelbaum, J. S., Wang, W., Anderson, C. S., Mendelow, A. D., Gregson, B., Janis, S., Vespa, P., Ziai, W., Zuccarello, M., & Awad, I. A. (2019). Efficacy and safety of minimally invasive surgery with thrombolysis in intracerebral haemorrhage evacuation (MISTIE III): a randomised, controlled, open-label, blinded endpoint phase 3 trial [Clinical Trial, Phase III; Journal Article; Multicenter Study; Randomized Controlled Trial]. *Lancet*, 393(10175), 1021-1032. http://doi.org/10.1016/S0140-6736(19)30195-3

Haseeb, A., Shafique, M. A., Mustafa, M. S., Singh, A., Iftikhar, S., Rangwala, B. S., Waggan, A. I., Fadlalla Ahmad, T. K., Raja, S., & Raja, A. (2024). Neuroendoscopic versus Craniotomy Approach in Supratentorial Hypertensive Intracerebral Hemorrhage: An Updated Meta-Analysis [Comparative Study; Journal Article; Meta-Analysis]. *World Neurosurgery*, 190, e721-e747. http://doi.org/10.1016/j.wneu.2024.07.212

Hemphill, J. R., Greenberg, S. M., Anderson, C. S., Becker, K., Bendok, B. R., Cushman, M., Fung, G. L., Goldstein, J. N., Macdonald, R. L., Mitchell, P. H., Scott, P. A., Selim, M. H., & Woo, D. (2015). Guidelines for the Management of Spontaneous Intracerebral Hemorrhage: A Guideline for Healthcare Professionals From the American Heart Association/American Stroke Association [Journal Article; Practice Guideline]. *Stroke*, 46(7), 2032-2060. http://doi.org/10.1161/STR.0000000000000069

Hostettler, I. C., Seiffge, D. J., & Werring, D. J. (2019). Intracerebral hemorrhage: an update on diagnosis and treatment [Journal Article; Research Support, Non-U.S. Gov't; Review]. *Expert Review of Neurotherapeutics*, 19(7), 679-694. http://doi.org/10.1080/14737175.2019.1623671

Hou, Y., Ma, L., Zhu, R., & Chen, X. (2016). iPhone-Assisted Augmented Reality Localization of Basal Ganglia Hypertensive Hematoma [Journal

Article]. *World Neurosurgery*, 94, 480-492. http://doi.org/10.1016/j.wneu.2016.07.047

Huang, X., Yan, Z., Jiang, L., Chen, S., & Liu, Y. (2023). The efficacy of stereotactic minimally invasive thrombolysis at different catheter positions in the treatment of small- and medium-volume basal ganglia hemorrhage (SMITDCP I): a randomized, controlled, and blinded endpoint phase 1 trial [Journal Article]. *Frontiers in Neurology*, 14, 1131283. http://doi.org/10.3389/fneur.2023.1131283

Jacopo, Scaggiante, Xiangnan, Zhang, J, Mocco, Christopher, P, & Kellner. (2018). Minimally Invasive Surgery for Intracerebral Hemorrhage. *Stroke*, 49(11), 2612-2620.

Kellner, C. P., Chartrain, A. G., Nistal, D. A., Scaggiante, J., Hom, D., Ghatan, S., Bederson, J. B., & Mocco, J. (2018). The Stereotactic Intracerebral Hemorrhage Underwater Blood Aspiration (SCUBA) technique for minimally invasive endoscopic intracerebral hemorrhage evacuation [Case Reports; Journal Article]. *Journal of Neurointerventional Surgery*, 10(8), 771-776. http://doi.org/10.1136/neurintsurg-2017-013719

Krylov, V. V., Burov, S. A., Dash'Ian, V. G., & Shaklunov, A. A. (2008). [Application of frameless neuronavigation in urgent neurosurgery] [Journal Article]. *Zh Vopr Neirokhir Im N N Burdenko*(3), 9-13, 14.

Labib, M. A., Shah, M., Kassam, A. B., Young, R., Zucker, L., Maioriello, A., Britz, G., Agbi, C., Day, J. D., Gallia, G., Kerr, R., Pradilla, G., Rovin, R., Kulwin, C., & Bailes, J. (2017). The Safety and Feasibility of Image-Guided BrainPath-Mediated Transsulcul Hematoma Evacuation: A Multicenter Study [Journal Article; Multicenter Study]. *Neurosurgery*, 80(4), 515-524. http://doi.org/10.1227/NEU.0000000000001316

Lian, M., Li, X., Wang, Y., Che, H., & Yan, Z. (2024). Comparison of two minimally invasive surgical approaches for hypertensive intracerebral hemorrhage: a study based on postoperative intracranial pressure parameters [Journal Article]. *Bmc Surgery*, 24(1), 10. http://doi.org/10.1186/s12893-023-02306-x

Liu, W. M., Zhang, X. G., Zhang, Z. L., Gang, L. I., & Huang, Q. B. (2017). Minimally invasive thalamic hematoma drainage can improve the six-month outcome of thalamic hemorrhage. *Journal of Geriatric Cardiology : Jgc*, 14(4), 266-273.

Lv, K., Wang, Y., Chao, H., Cao, S., & Cao, W. (2023). Comparison of the Efficacy of Subosseous Window Neuro-Endoscopy and Minimally Invasive Craniotomy in the Treatment of Basal Ganglia Hypertensive Intracerebral Hemorrhage [Journal Article]. *Journal of Craniofacial Surgery*, 34(8), e724-e728. http://doi.org/10.1097/SCS.0000000000009461

Miao, X. L., Wang, Z. G., Yang, W. D., Zhao, Y., Chen, Z. J., Yu, F. H., Yue, S. Y., Zhang, J. N., & Yu, Q. (2012). [Application of high-field intraoperative magnetic resonance imaging in stereotactic aspiration and drainage of hypertensive hematomas] [English Abstract; Journal Article; Research

Support, U.S. Gov't, Non-P.H.S.]. *中华医学杂志*, 92(35), 2491-2494.

Norton, Isaiah, Essayed, I., Walid, Zhang, Pujol, Sonia, Yarmarkovich, Alex, & Golby. (2017). SlicerDMRI: Open Source Diffusion MRI Software for Brain Cancer Research, 77(21), e101.

Tang, C., Zhang, M., & Li, W. (2023). Meta-analysis of stereotactic hematoma removal and craniotomy hematoma removal in the treatment of hypertensive intracerebral hemorrhage in the elderly [Journal Article; Meta-Analysis]. *Medicine*, 102(49), e36533. http://doi.org/10.1097/MD.0000000000036533

UMEBAYASHI, D., MANDAI, A., OSAKA, Y., NAKAHARA, Y., & TENJIN, H. (2010). Effects and Complications of Stereotactic Aspiration for Spontaneous Intracerebral Hemorrhage [Journal Article]. *Neurologia Medico-Chirurgica*, 50(7), 538-544. http://doi.org/10.2176/nmc.50.538

Wang, W., Jiang, C., & Bai, H. (2015). New Insights in Minimally Invasive Surgery for Intracerebral Hemorrhage. *Frontiers of Neurology and Neuroscience*, 37(January), 155. http://doi.org/10.1159/000437120

Wu, S., Wang, H., Wang, J., Hu, F., Jiang, W., Lei, T., & Shu, K. (2021). Effect of Robot-Assisted Neuroendoscopic Hematoma Evacuation Combined Intracranial Pressure Monitoring for the Treatment of Hypertensive Intracerebral Hemorrhage [Journal Article]. *Frontiers in Neurology*, 12, 722924. http://doi.org/10.3389/fneur.2021.722924

X., Zhou, J., Chen, Q., Li, G., Ren, G., & Yao. (2012). Minimally Invasive Surgery for Spontaneous Supratentorial Intracerebral Hemorrhage: A Meta-Analysis of Randomized Controlled Trials. *Stroke*, 43(11), 2923-2930.

Xie, Q., Zhang, X., Ding, Y., & Zhang, L. (2024). Assessing the Clinical Efficacy of Stereotactic Puncture in Combination with Postoperative Rehabilitation Training for Hypertensive Cerebral Hemorrhage [Journal Article]. *Alternative Therapies in Health and Medicine*, 30(6), 122-127.

Xiong, J., Chen, Y., Wang, R., Hu, S., Xu, J., Mo, X., Li, X., Zhou, Y., Guan, C., Huang, J., & Su, F. (2024). Minimally invasive puncture combined with a high frequency of urokinase therapy improves outcomes in patients with HICH [Journal Article]. *Neurotherapeutics*, 21(1), e00293. http://doi.org/10.1016/j.neurot.2023.10.003

Xu, X., Chen, X., Zhang, J., Zheng, Y., Sun, G., Yu, X., & Xu, B. (2014). Comparison of the Tada formula with software slicer: precise and low-cost method for volume assessment of intracerebral hematoma [Comparative Study; Journal Article; Research Support, Non-U.S. Gov't]. *Stroke*, 45(11), 3433-3435. http://doi.org/10.1161/STROKEAHA.114.007095

Xu, X., Zhang, H., Zhang, J., Luo, M., Wang, Q., Zhao, Y., Gan, Z., Xu, B., & Chen, X. (2024). Minimally invasive surgeries for spontaneous hypertensive intracerebral hemorrhage (MISICH): a multicenter randomized controlled trial [Journal Article; Multicenter Study; Randomized Controlled Trial]. *Bmc Medicine*, 22(1),

244. http://doi.org/10.1186/s12916-024-03468-y

Yan, Y. F., Ru, D. W., Du JR, Shen, X., Wang, E. S., & Yao, H. B. (2015). The clinical efficacy of neuronavigation-assisted minimally invasive operation on hypertensive basal ganglia hemorrhage [Journal Article; Research Support, Non-U.S. Gov't]. *European Review for Medical and Pharmacological Sciences*, 19(14), 2614-2620.

Yao, S., Zhang, J., Zhao, Y., Hou, Y., Xu, X., Zhang, Z., Kikinis, R., & Chen, X. (2018). Multimodal Image-Based Virtual Reality Presurgical Simulation and Evaluation for Trigeminal Neuralgia and Hemifacial Spasm [Evaluation Study; Journal Article]. *World Neurosurgery*, 113, e499-e507. http://doi.org/10.1016/j.wneu.2018.02.069

Yu, G., Sx, A., Xl, A., & Xm, A. (2019). Preliminary study on Sina (Sina Intraoperative Neurosurgical Assist) APP assisted localization of supratentorial lesions by smart phone. *Journal of Clinical Neuroscience*, 62, 277-281.

Zhang, L., Xu, L., Jing, S., & Liang, L. (2024). Efficacy of Neuroendoscopy Surgery Combined With Postoperative Lokomat Rehabilitation Training in Patients With Hypertensive Intracerebral Hemorrhage [Journal Article]. *Journal of Craniofacial Surgery* http://doi.org/10.1097/SCS.0000000000010358

Zhang, X., Xiao, G., Xu, X., Zhang, C., Liu, C., & Cao, Y. (2012). A case report and DSA findings of cerebral hemorrhage caused by syphilitic vasculitis [Case Reports; Journal Article]. *Neurological Sciences*, 33(6), 1411-1414. http://doi.org/10.1007/s10072-011-0887-7

Zhao, H., Zhang, T., Li, M., Gao, Y., Wang, S., Jiang, R., & Li, Z. (2023). Three-dimensional laser combined with C-arm computed tomography-assisted puncture of intracerebral hemorrhage [Journal Article; Research Support, Non-U.S. Gov't]. *Frontiers in Endocrinology*, 14, 1198564. http://doi.org/10.3389/fendo.2023.1198564

Zhou, H., Zhang, Y., Liu, L., Huang, Y., Tang, Y., Su, J., Hua, W., Han, X., Xue, J., & Dong, Q. (2011). Minimally invasive stereotactic puncture and thrombolysis therapy improves long-term outcome after acute intracerebral hemorrhage [Clinical Trial; Journal Article; Randomized Controlled Trial; Research Support, Non-U.S. Gov't]. *Journal of Neurology*, 258(4), 661-669. http://doi.org/10.1007/s00415-011-5902-7

Zhu, H., Shi, W., & Wang, Z. (2010). Keyhole endoscopic hematoma evacuation in patients [Case Reports; Journal Article]. *Turkish Neurosurgery*, 22(3), 294-299. http://doi.org/10.5137/1019-5149.JTN.5136-11.1

Zou, D., Chen, X., Chen, S., Zhang, P., & Lu, Y. (2024). Impact of Endoscopic Surgery Versus Robot CAS-R-2 Assisted with Stereotactic Drainage on Prognosis of Basal Ganglia Hypertensive Intracerebral Hemorrhage [Journal Article; Observational Study]. *World Neurosurgery*, 181, e589-e596. http://doi.org/10.1016/j.wneu.2023.10.097