Am J Transl Res 2025;17(11):8623-8632
www.ajtr.org /ISSN:1943-8141/AJTR0167598

*Original Article*

# Clinical benefit of robot-assisted minimally invasive stereotactic aspiration/drainage in hypertensive intracerebral hemorrhage

Jun Ding, Yiming Zhang, Guowei Jiang, Jian Shi, Kui Ma, Pengcheng Deng, Lianfu Zhang

*Department of Neurosurgery, Anhui No. 2 Provincial People's Hospital, Hefei 230041, Anhui, China*

Received July 21, 2025; Accepted October 20, 2025; Epub November 15, 2025; Published November 30, 2025

**Abstract:** Objective: To evaluate the efficacy of robot-assisted minimally invasive stereotactic aspiration/drainage (RAMISAD) in hematoma evacuation for hypertensive intracerebral hemorrhage (HICH) and assess its associated clinical benefits. Methods: A retrospective analysis was conducted on 121 HICH patients admitted between October 2020 to March 2025. According to surgical procedures, patients were categorized into a control group (n=62, conventional craniotomy for hematoma evacuation) and an observation group (n=59, RAMISAD). Surgical factors, neurological recovery (National Institutes of Health Stroke Scale, NIHSS), daily living function (Barthel Index), and pre- and post-operative serum markers (neuron-specific enolase [NSE], tumor necrosis factor-α [TNF-α], and high-sensitivity C-reactive protein [hs-CRP]) were compared between groups. Complication rates were also documented postoperatively. Results: The hematoma clearance rate was significantly higher in the observation group than in the control group. RAMISAD was associated with shorter operative time, reduced blood loss, and shorter hospital stays ($P<0.05$). No significant differences were observed in residual hematoma volumes or transfusion rates ($P>0.05$), and all postoperative hematoma volumes remained below the 30 mL safety threshold. On postoperative day 7, serum NSE, TNF-α, and hs-CRP levels decreased more markedly in the observation group than in controls ($P<0.05$). After three-months, the observation group displayed significantly reduced NIHSS scores and elevated Barthel Index scores compared to the control group ($P<0.05$). Additionally, complications occurred less frequently in the observation group ($P<0.05$). Conclusion: For HICH cases, RAMISAD offers clear advantages over traditional craniotomy, including improved hematoma evacuation efficiency, reduced neurological impairment, enhanced functional recovery, and lower postoperative inflammatory responses, thereby promoting faster rehabilitation.

**Keywords:** Robot-assisted, stereotactic, minimally invasive aspiration/drainage, HICH, hematoma clearance effect

## Introduction

Hypertensive intracerebral hemorrhage (HICH) is a severe neurological emergency characterized by sudden onset and rapid progression [1]. International research indicates that HICH predominantly affects middle-aged and elderly individuals, with a slight male predominance. Approximately 35% to 52% of patients die within 30 days of onset, and the 6-month mortality rate ranges from 23% to 58% [2]. Conventional craniotomy enables direct hemostasis under visualization and is applicable to patients with intracranial hypertension or cerebral herniation. Nonetheless, the procedure requires extensive brain tissue exposure, is time-consuming, and carries a high risk of complications such as intracranial infection and rebleeding. When standard craniotomy is unsuitable or ineffective, hematoma aspiration and drainage are often preferred for their minimal invasiveness and procedural simplicity. Since the late 1990s, the YL-1 puncture needle has been widely applied for intracranial hematoma treatment in China, because of its quick operations, effective hematoma aspiration, and excellent safety profile [3, 4]. However, active bleeding during or after the procedure cannot be effectively controlled, and deviations in puncture positioning may occur, limiting its overall efficacy. With the advancement of stereotactic navigation and the growing emphasis on minimally invasive neurosurgery, robot-assisted stereotactic techniques have emerged as a promising alternative for HICH management. In recent years, evidence supports the therapeutic value

https://doi.org/10.62347/ZFEG5216

**Table 1.** Comparison of baseline information between the two groups [($\overline{x}$±S), *M* (*IQR*), *n* (%)]

| | Control group (n=62) | Observation group (n=59) | t/$\chi^2$/Z | *P* |
|---|---|---|---|---|
| Age (years) | 56.44±14.00 | 57.53±13.87 | -0.430 | 0.668 |
| Male/female (n) | 43/19 | 43/16 | 0.183 | 0.669 |
| GCS on admission (points) | 10.25±3.07 | 10.89±3.14 | 1.134 | 0.259 |
| Hematoma volume (mL) | 30.00 (12.00) | 30.00 (15.00) | -0.281 | 0.778 |
| Hematoma location | | | 0.340 | 0.844 |
| Basal ganglia | 23 (37.10) | 20 (33.90) | | |
| Thalamus | 19 (30.65) | 21 (35.59) | | |
| Subcortical | 20 (32.26) | 18 (30.51) | | |
| Hypertension history (years) | 10.63±2.53 | 11.05±3.17 | 0.807 | 0.421 |
| Muscle strength on admission (n) | | | 0.103 | 0.749 |
| 0-II | 49 (79.03) | 48 (81.36) | | |
| III-IV | 13 (20.97) | 11 (18.64) | | |

Note: GCS: Glasgow Coma Scale.

of stereotactic soft-channel puncture and hematoma drainage for treating HICH. Drawing from these earlier studies, this research evaluates the effectiveness and advantages of robot-assisted minimally invasive stereotactic aspiration/drainage (RAMISAD) for hematoma evacuation in patients with HICH.

## Materials and methods

### *General information*

From October 2020 to March 2025, the clinical records of 121 patients diagnosed with HICH at Anhui No. 2 Provincial People's Hospital were retrospectively reviewed. Based on the surgical procedure performed, these patients were categorized into two groups: the control group (n=62, conventional craniotomy) and the observation group (n=59, RAMISAD). In the control group (43 males, 19 females), the participants were aged from 28 to 81 years (with an average age of 56.44±14.00 years), with hematoma volumes of 10-65 mL (median 30.00 mL, IQR 12.00 mL). In the observation group (43 males, 16 females), the patients were aged 28 to 81 years, with a mean age of (57.53±13.87) years, and hematoma volumes were 10-60 mL (median 30.00 mL, IQR 15.00 mL). There were no significant intergroup differences in age, Glasgow Coma Scale (GCS) scores, or hematoma volume (P>0.05). Detailed baseline data are presented in **Table 1**.

Inclusion criteria: 1) Hypertension diagnosis per *the Chinese Guidelines for the Prevention and Treatment of Hypertension* [5] and *Internal Medicine* [6]; 2) HICH confirmed by computed tomography (CT) or magnetic resonance imaging (MRI); 3) Complete clinical and imaging data; 4) Eligibility for surgical intervention; 5) Admission within 24 h of symptom onset; and 6) Approval by the hospital ethics committee. Exclusion criteria: 1) Coagulopathy or immune dysfunction; 2) Hemorrhage secondary to stroke or intracranial aneurysms; 3) Severe hemorrhagic shock; 4) Vascular malformations (confirmed b y Digital Subtraction Angiography [DSA] or MRI), hydrocephalus, or related complications.

Surgical indications [7] included supratentorial hematoma volume >30 mL; cerebellar hematoma volume >10 mL or diameter >3 cm; progressive neurologic deterioration (≥2-point reduction on GCS) or refractory intracranial hypertension even when hematoma volume did not reach the above thresholds; and imaging evidence of >5 mm midline shift or herniation signs. All physicians reached a consensus when evaluating surgical eligibility.

### *Methods*

All patients received standard symptomatic interventions, including supplemental oxygen, antihypertensive therapy, nutritional support, prophylactic antibiotics, and internal homeostasis maintenance.

Observation group: Patients in this group underwent stereotactic minimally invasive hematoma aspiration and drainage assisted by the domestic Remebot RM-100 neurosurgical robot. Prior to surgery, 4-5 cranial fiducial markers were affixed to the patient's scalp, followed by thin-slice CT scanning (1.0 mm slice thickness). Based on the CT data, a hematoma model was then reconstructed to determine the optimal puncture target and trajectory. A "verification target" was then selected, and the robotic arm automatically navigated to the designated validation point. The system's positioning accuracy was confirmed within a 2-millimeter tolerance. Under general anesthesia, the patient's head was immobilized to ensure the robotic arm operated within the defined surgical zone. The preplanned trajectory was uploaded to the navigation system, and the scalp puncture site was marked. Following standard disinfection procedures, a linear scalp incision approximately 3 cm was made at the designated entry point. Subsequently, a cranial perforation (10-12 mm in diameter) was drilled, and the dura mater was incised. The drilling depth was preset according to the hematoma's location and morphology, ensuring precision through robotic guidance. Through the navigated channel, a 10-Fr drainage catheter was then advanced along planned trajectory to the calculated target coordinates. Liquefied hematoma contents were aspirated using a 5-mL syringe. If the aspirated volume deviated significantly from the preoperative estimate, the catheter depth or side-port orientation was adjusted accordingly. Normal saline irrigation was performed with volumes not exceeding 20 mL per rinse. Once no fresh bleeding was observed, the drainage tube was retained in situ within the hematoma cavity. Following surgery, the patients were transferred to the intensive care unit (ICU) for continuous monitoring and management. Routine follow-up CT scan were performed to assess hematoma clearance. The decision to administer urokinase was based on postoperative imaging findings (residual hematoma volume and configuration), drainage fluid characteristics, and clinical judgment [7]. In cases of significant residual hematoma, 30,000 to 50,000 units of urokinase were administered into the cavity once or twice daily until satisfactory evacuation was achieved. The drainage tube was generally removed within 2-3 days. Patients were transferred to the general ward for routine postoperative care and early rehabilitation once their physiological indicators stabilized and neurological function improved.

Control group: Patients in the control group underwent conventional craniotomy for hematoma evacuation under general anesthesia with endotracheal intubation. The hematoma location was identified based on preoperative cranial CT findings. A curvilinear or horseshoe-shaped incision was made around the surface projection of the hematoma, and a bone flap measuring approximately 5-8 cm in diameter was created to fully expose the lesion area. After the dura mater was radially incised, a 2-3 cm cortical incision (corticotomy) was made in the nearest non-functional regions (e.g., middle frontal gyrus or superior temporal gyrus). Under direct vision, the hematoma was evacuated using gentle suction, and meticulous hemostasis was achieved. Intraoperative hemorrhage control adhered to strict protocols: bipolar coagulation was used for active arterial or spot bleeding, whereas gelatin sponge or hemostatic gauze were applied to control diffuse parenchymal oozing. The surgical cavity was repeatedly irrigated with normal saline, with suturing performed afterward. Post-surgery, the patients' vital signs were closely monitored, and comprehensive treatments like nutritional support and anti-infection measures were provided.

All surgical procedures in this investigation, both RAMISAD and conventional open craniotomies, were performed by experienced attending neurosurgeons or associate chief physicians (or higher). The choice of surgical technique was made collaboratively by a senior multidisciplinary team based on objective clinical factors such as hematoma size, location, and patient condition, together with informed patient consent, rather than individual surgeon preference.

*Outcome measures*

*Surgical outcomes:* Hematoma clearance rate, intraoperative blood loss, operative duration, length of hospital stay, residual hematoma volume, proportion of patients with residual hematoma volume <30 mL, and blood transfusion rate were recorded. The clearance rate was calculated as: [(preoperative volume - postoperative 24 h residual volume)/preoperative volume] × 100%. According to established transfusion protocols [8], packed red blood cells were administered when intra- or post-operative hemoglobin (Hb) levels dropped below

70-80 g/L, or the presence of active bleeding with hypovolemic symptoms (e.g., increased heart rate, decreased blood pressure). For elderly patients or those with severe cardio/cerebrovascular disease (e.g., coronary artery disease, cerebral insufficiency), the transfusion threshold was raised to Hb <90-100 g/L to maintain adequate organ perfusion.

*Neurological function and activities of daily living (ADL):* Neurological deficits were assessed by neurosurgeons using the National Institutes of Health Stroke Scale (NIHSS) both preoperatively and at 3 months postoperatively, with higher scores indicating more severe impairment [9]. Functional independence in activities of daily living was evaluated using the Barthel Index Rating Scale [10], where higher scores denote greater self-care ability and functional recovery.

*Serum biomarkers:* Venous blood samples (5 mL) were collected from fasting patients before surgery and on postoperative day 7. Samples were centrifuged at 3000 r/min for 10 minutes. The isolated serum was subjected to enzyme-linked immunosorbent assay (ELISA) for the measurement of hypersensitive-C reactive protein (hs-CRP), tumor necrosis factor-α (TNF-α), and neuron-specific enolase (NSE). All assay kits were sourced from Zhejiang Medicalsystem Biotechnology Co., Ltd., and procedures were performed in strict accordance with the manufacturer's instructions.

*Postoperative complications:* The incidence of postoperative complications, including intracranial infections, deep vein thrombosis, and stress ulcers, was documented. The diagnostic criteria for post-operative intracranial infections were based on previous research [11], encompassing: 1) clinical signs of infection (e.g., fever, neck stiffness); and 2) at least one of the following: positive cerebrospinal fluid (CSF) bacterial culture; or CSF white blood cell count >100 × $10^6$/L (predominantly polymorphonuclear leukocytes) accompanied by either CSF glucose <2.25 mmol/L or protein >0.45 g/L.

*Statistical methods*

All statistical analyses were performed using SPSS 18.0. Quantitative data conforming to a normal distribution were expressed as mean ± standard deviation ($\bar{X}$±S), and between-group comparisons were conducted using independent-samples t-tests. For skewed quantitative data, results were expressed as median (interquartile range) [M (IQR)], and comparisons were made using non-parametric Wilcoxon rank-sum tests. Categorical variables were presented as percentages (%), and differences between groups were analyzed using $\chi^2$ test or Fisher's exact test when expected frequencies were <5. A two-tailed *P*<0.05 was considered significant. A post hoc power analysis was conducted using G*Power 3.1 (α=0.05, power =80%, allocation ~1:1). The minimum required sample size was 55 participants per group. In this study, 121 participants were included (62 in the control group, and 59 in the observation group), providing an achieved statistical power of 83.1%, thereby satisfying the test requirements. The minor intergroup size difference (<5%) remained within the tolerance threshold of nonparametric tests such as the Mann-Whitney U test, which is robust to small imbalances. Therefore, the non-significant findings (P>0.05) observed for certain outcomes were unlikely to be attributable to insufficient sample size.

## Results

*Surgical outcomes*

Surgical outcomes indicated that the hematoma evacuation was more effective in the observation group. Compared to the control group, patients treated with RAMISAD experienced significantly reduced intraoperative blood loss and shorter operative and hospitalization durations (*P*<0.05). No significant intergroup differences were observed in residual hematoma volume and blood transfusion rate (*P*>0.05). Importantly, residual hematoma volumes were below the 30 mL safety benchmark in both cohorts (**Table 2**).

*Effect of robot-assisted hematoma clearance*

Follow-up cranial CT scans were performed in all patients before drainage catheter removal. Imaging results confirmed satisfactory hematoma evacuation, with substantial reduction or complete resolution of the mass effect (**Figures 1-3**).

**Table 2.** Comparison of surgical parameters between the two groups ($\overline{X}\pm S$)

| | Control group (n=62) | Observation group (n=59) | t/Fisher's | *P* |
|---|---|---|---|---|
| Intraoperative blood loss (mL) | 158.63±42.35 | 102.39±31.07 | 8.294 | <0.001 |
| Operative duration (min) | 77.24±18.15 | 55.83±14.21 | 7.200 | <0.001 |
| Hospital stay duration (d) | 17.23±4.58 | 12.47±3.91 | 6.134 | <0.001 |
| Hematoma clearance rate (%) | 90.46±4.08 | 92.41±5.95 | 2.111 | 0.037 |
| Residual hematoma volume (mL) | 2.22±1.52 | 2.66±1.25 | 1.743 | 0.084 |
| Residual hematoma volume <30 mL (%) | 62 (100) | 59 (100) | - | - |
| Blood transfusion rate (%) | 5 (8.06) | 2 (3.39) | - | 0.440 |

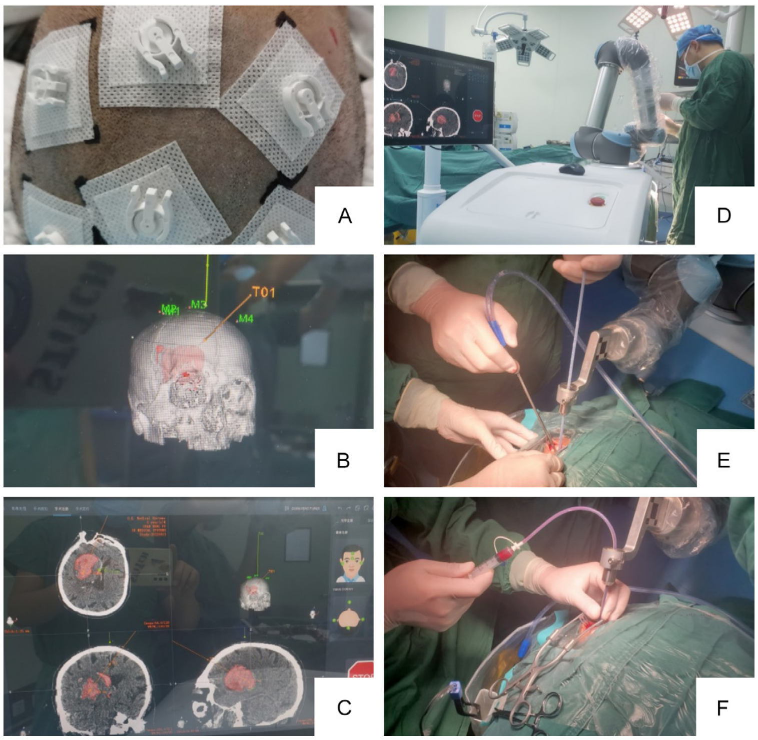


**Figure 1.** Robot-assisted minimally invasive stereotactic aspiration/drainage procedures. Note: (A) (Marker placement and CT scanning): The surgical site was shaved, sterilized, and fitted with cranial fiducial markers. Thin-slice CT imaging (covering the cranial vertex to the labial region) was subsequently performed. (B) (Preoperative planning): CT data were imported into the robotic planning system to reconstruct three-dimensional models of intracranial structures. Surgeons then identified the optimal puncture target and trajectory to minimize injury to functional brain regions and major vessels. (C) (Incision localization): The planned trajectory was verified intraoperatively to simulate puncture alignment, allowing accurate localization of the surgical incision site. (D-F) (Surgical procedures): A standard craniotomy was executed as per the preoperatively localized incision. Under robotic stereotactic guidance, was employed for hematoma puncture. Upon reaching the target location, the hematoma was punctured, and a 5-mL syringe was used to aspirate the hematoma contents upon reaching the target site.

*Serum biomarkers*

On postoperative day 7, serum levels of NSE, TNF-α, and hs-CRP were significantly lower in the observation group compared to the control group (*P*<0.05; **Table 3**).

*Neurological recovery and ADL*

At three months postoperatively, patients in the observation group exhibited significantly lower NIHSS scores and higher Barthel Index scores than those in the control group (*P*<0.05; **Table 4**). These results indicate that RAMISAD contributed to improved neurological recovery and enhanced functional independence.

*Complication rates*

The observation group reported significantly fewer overall incidence of postoperative complications than in the control group (*P*<0.05; **Table 5**). One case of intracranial infection (1.69%) occurred in the observation group, which was confirmed by CSF analysis and resolved completely after intravenous administration of vancomycin and meropenem. In the control group, two patients experienced postoperative rebleeding, both requiring repeat craniotomy - one due to difficult hemostasis during surgery, and the other resulting from inadequate postoperative hypertension control. In contrast, two rebleeding events also occurred in the observation group but were managed less invasively: one caused by drainage catheter malposition was corrected

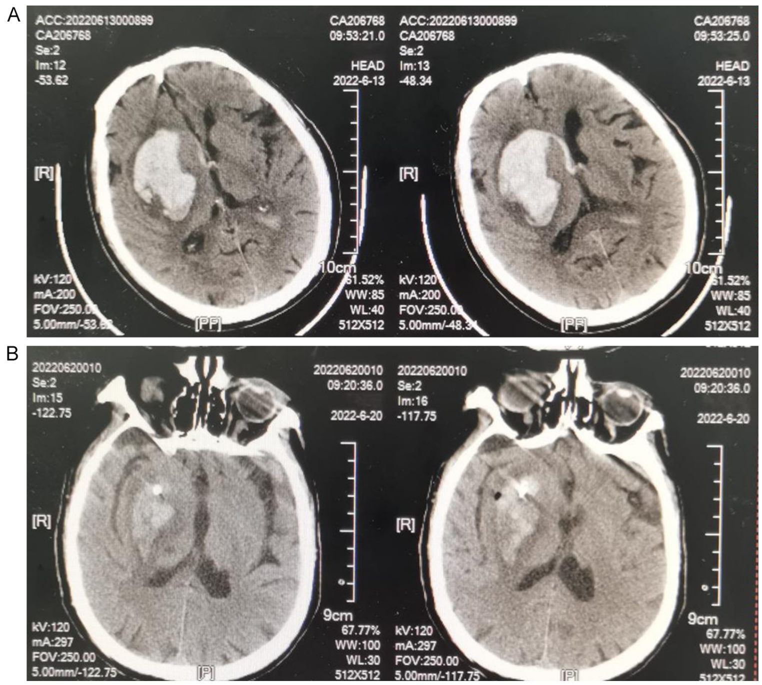


**Figure 2.** Preoperative and postoperative Computed Tomography (CT) scans of basal ganglia lateral region hemorrhages. Note: (A) Preoperative CT imaging. (B) Postoperative CT imaging at 48-hour follow-up.

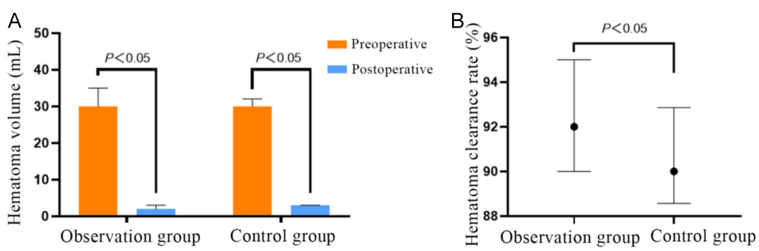


**Figure 3.** Comparison of hematoma clearance between the two groups. A. Comparison of pre- and postoperative hematoma volumes. B. Comparison of hematoma clearance rate between groups.

under CT guidance with adjunctive thrombolytic therapy, and the other, due to postoperative hypertension, was managed conservatively without reoperation.

## Discussion

Spontaneous intracerebral hemorrhage affects approximately 2 million individuals annually in China, with HICH comprising the majority (70%) [12]. Following hemorrhage, a relatively stable hematoma develops, producing mechanical compression that directly damages surrounding brain tissue. This triggers massive release of thrombin and other pro-inflammatory factors, contributing to secondary neuronal injury [13, 14]. Earlier research has demonstrated that early hematoma evacuation can not only alleviate the mass effect but also restore cerebral perfusion in the perihematomal zone, thereby reducing neurological deficits and improving functional recovery [15].

The prognosis of HICH is closely related to hematoma volume. Surgical management is indicated when the hematoma diameter exceeds 4 cm, the bleeding volume surpasses 30 ml, or when brainstem compression and obvious midline shift are present [16]. Craniotomy allows direct visualization of the hematoma cavity, enabling complete hematoma evacuation and intraoperative hemostasis. It also provides the opportunity for decompression in patients with significant cerebral edema or critical neurological deterioration. However, the procedure is associated with considerable drawbacks, including substantial iatrogenic brain injury, high anesthesia requirement, and a high incidence of postoperative complications. Consequently, minimally invasive surgery is often preferred for patients with small- to medium-sized hematomas or limited physiological tolerance. Stereotactic techniques enable the design of precise and efficient puncture trajectories by incorporating data on hematoma size, configuration, adjacent anatomy, and bleeding source. These methods enhance the success rate of lesion targeting while minimizing intraoperative injury [17]. The modern era of HICH management began in 1978 when Backlund first implemented stereotactic technology for intracerebral hematoma evacuation, introducing the novel concept of controlled subtotal hematoma evacuation [18]. While stereotactic aspiration and drainage are now widely utilized, robot-assisted versions of these procedures remain relatively underreported.

**Table 3.** Comparison of serum-related indices between the two groups ($\overline{X}$±S)

| Group | n | NSE (μg/L) | | *t* value | *P* value | TNF-α (ng/ml) | | *t* value | *P* value | hs-CRP (mg/L) | | *t* value | *P* value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Preoperative | 7 days postoperatively | | | Preoperative | 7 days postoperatively | | | Preoperative | 7 days postoperatively | | |
| Control group | 62 | 48.63±12.74 | 28.66±7.31 | 10.705 | <0.001 | 27.51±6.39 | 18.03±5.61 | 8.778 | <0.001 | 13.26±4.59 | 7.15±2.39 | 3.571 | <0.001 |
| Observation group | 59 | 49.18±14.21 | 24.15±6.82 | 12.198 | <0.001 | 28.72±7.04 | 14.94±5.15 | 12.135 | <0.001 | 12.84±5.03 | 4.54±1.02 | 12.422 | <0.001 |
| *t* value | - | 0.224 | 3.505 | - | - | 0.991 | 3.152 | - | - | 0.480 | 7.743 | - | - |
| *P* value | - | 0.823 | <0.001 | - | - | 0.324 | 0.002 | - | - | 0.632 | <0.001 | - | - |

Note: NSE, neuron-specific enolase; TNF-α, tumor necrosis factor-α; hs-CRP, hypersensitive-C reactive protein.

**Table 4.** Comparison of NIHSS and Barthel Index scores between the two groups ($\overline{X}$±S)

| Group | n | NIHSS score | | *t* value | *P* value | Barthel index score | | *t* value | *P* value |
|---|---|---|---|---|---|---|---|---|---|
| | | Preoperative | 3 months postoperatively | | | Preoperative | 3 months postoperatively | | |
| Control group | 62 | 19.71±3.37 | 14.35±2.13 | 10.586 | <0.001 | 22.36±5.38 | 53.62±9.55 | 22.456 | <0.001 |
| Observation group | 59 | 20.19±4.04 | 10.92±2.65 | 14.737 | <0.001 | 21.75±6.02 | 59.82±11.07 | 23.206 | <0.001 |
| *t* value | - | 0.711 | 7.866 | - | - | 0.588 | 3.304 | - | - |
| *P* value | - | 0.478 | <0.001 | - | - | 0.557 | 0.001 | - | - |

Note: NIHSS (National Institutes of Health Stroke Scale) evaluates stroke-related neurological impairment, while the Barthel Index quantifies independence in daily activities.

**Table 5.** Comparison of complication rates between the two groups [n (%)]

| Group | n | Deep vein thrombosis | Stress ulcers | Intracranial infections | Pulmonary infections | Rebleeding | Total incidence |
|---|---|---|---|---|---|---|---|
| Control group | 62 | 7 (11.29) | 3 (4.84) | 4 (6.45) | 3 (4.84) | 2 (3.23) | 19 (30.65) |
| Observation group | 59 | 2 (3.39) | 3 (5.08) | 1 (1.69) | 1 (1.69) | 2 (3.39) | 9 (15.25) |
| $\chi^2$ value | - | - | - | - | - | - | 4.026 |
| *P* value | - | - | - | - | - | - | 0.045 |

In the present study, RAMISAD achieved superior surgical outcomes compared to craniotomy. Several factors contribute to this outcome: (1) The robotic navigation system provided exceptional precision in trajectory planning and catheter placement. Preoperative customization of puncture paths based on hematoma morphology and location optimized drainage efficiency while significantly shortening operative duration; (2) The flexible catheter design permitted multi-point aspiration with adjustable side-port orientation and insertion depth, maximizing hematoma contact area while minimizing direct disruption of adjacent brain tissue and vessels. This approach improved clearance and safety; (3) Sequential liquefying, irrigation, and drainage of the hematoma cavity diluted local toxic metabolites and inflammatory mediators, reducing secondary brain edema and expediting recovery; (4) For cases involving firm hematomas, a fragmentation needle (YL-2) facilitated mechanical clot disruption, ensuring more thorough hematoma clearance. Functionally, patients treated with RAMISAD demonstrated significantly lower NIHSS scores and higher Barthel Index scores at 3-months postoperatively, which agrees with the findings of Han et al. [7]. Compared to conventional craniotomy, RAMISAD minimizes cortical exposure and mechanical traction, as the cortical puncture diameter measures only 2-3 mm under robotic guidance, markedly reducing cerebral injury [19, 20]. Craniotomy-related trauma often involves disruption of the frontal pontine tract of the anterior branch of the internal capsule, which may induce ataxia and impair long-term motor recovery. As noted by Jiang [21], neuronal degeneration and necrosis begin within 6-7 hours after hematoma formation, driven by mechanical compression, ischemia, and release of vasoactive substances. This cascade leads to secondary ischemic and edematous changes in perihematomal tissue. Among biochemical indicators, hs-CRP acts as an acute-phase reactant reflecting inflammation intensity and tissue damage; elevated hs-CRP levels in HICH patients correlate with worse neurological outcomes [22]. NES, released into the bloodstream after blood-brain barrier disruption, serves as a reliable biomarker for neuronal injury. TNF-α, a key inflammatory cytokine, promotes leukocyte migration and endothelial dysfunction and plays a pivotal role in post-hemorrhagic neuroinflammation [23-25]. This study found that serum levels of NSE, TNF-α, and hs-CRP on postoperative day 7 were significantly lower in the observation group compared to the control group, suggesting the superiority of RAMISAD to conventional craniotomy in preserving cerebral microcirculation and mitigating nerve cell damage. These findings underscore the biological advantages of RAMISAD: accurate targeting minimizes collateral tissue disruption, while a small incision reduces systemic inflammatory stress. In addition, patients treated with RAMISAD experienced significantly fewer postoperative complications. This may be attributed to minimized brain tissue exposure and the use of gelatin-based sealing with the hematoma cavity, which enhances local hemostasis and reduces rebleeding risk.

Comparative analyses have been conducted between RAMISAD and other minimally invasive technologies (e.g., neuroendoscope-guided surgery) in patients with intracerebral hemorrhage. Tan et al. [26] reported that, for spontaneous intracerebral hemorrhage, RAMISAD offers greater surgical efficiency and cost-effectiveness than neuroendoscopic procedures. Similarly, Wu et al. [27] reported that in HICH patients, RAMISAD combined with intracranial pressure monitoring provides superior therapeutic efficacy and safety compared with neuroendoscopic-assisted surgery. Conversely, a study focusing on basal ganglia HICH found that neuroendoscopic-assisted surgery yielded more favorable six-month prognostic results than RAMISAD [28].

Despite these promising findings, certain limitations exist. First, as a retrospective analysis, the dataset was incomplete for certain time points; specifically, postoperative 1-month NIHSS and Barthel Index data were unavailable, which limited the assessment of early functional recovery trends. Second, serum levels of NSE, TNF-α, and hs-CRP within 24 hours after surgery were not collected. Incorporating these data would enhance understanding of the acute inflammatory response following intervention. Third, there is a paucity of long-term (>6 months) follow-up data, preventing a comprehensive evaluation of sustained neurological and functional outcomes. Future multicenter, prospective studies with extended observation periods are warranted to validate the long-term prognostic benefits of RAMISAD. Finally, an economic analysis comparing RAMISAD to other surgical modalities was not performed. A detailed cost-benefit evaluation would provide valuable evidence to support the broader clinical adoption of this technology.

## Conclusion

RAMISAD demonstrated clear superiority over conventional craniotomy in HICH management. This technique enabled more efficient hematoma evacuation, greater mitigation of neurological deficits, improved ADL, and significant reductions in serum hs-CRP, NSE, and TNF-α, collectively accelerating the 3-month postoperative recovery. However, as this study was retrospective in design, the findings should be interpreted with caution. Future large-scale, prospective, multi-center studies are warranted to further validate the therapeutic efficacy, long-term outcomes, and cost-effectiveness of RAMISAD for HICH treatment.

## Acknowledgements

Clinical study on the surgical treatment of hypertensive cerebral hemorrhage using neuroendoscope combined with 3D-slicer software technology, project number: 2024AH050539; Application research of robot-assisted minimally invasive puncture in the treatment of small-volume thalamic hemorrhage, project number: 2024AH050544.

## Disclosure of conflict of interest

None.

**Address correspondence to:** Lianfu Zhang, Department of Neurosurgery, Anhui No. 2 Provincial People's Hospital, Hefei 230041, Anhui, China. Tel: +86-0551-64272137; E-mail: mumu2825@126.com

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