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Research Article

Robot-assisted stereotactic puncture and drainage for massive intracranial hematomas: analysis of evacuation volume threshold and clinical efficacy

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Abstract

Objective: To investigate the impact of postoperative residual hematoma volume threshold (15 mL) on clinical efficacy in robot-assisted stereotactic puncture and drainage (RA-SPD) for spontaneous large-volume intracranial hematomas(≥60ml).

Methods: A retrospective analysis of 89 patients undergoing RA-SPD was conducted. Patients were stratified by residual hematoma volume: Observation Group (>15 mL, n=49) vs. Control Group (≤15 mL, n=40). Comparisons included ICU/hospital stays, 6-month NIHSS/GCS/Barthel scores, complication rates in non-rebleeding patients, plus rebleeding incidence and total costs.

Results: Among non-rebleeding patients, no significant differences existed in ICU/hospital stays, neurological scores (NIHSS/GCS/Barthel), or rates of intracranial/pulmonary infections/hydrocephalus (all P>0.05). The Observation Group demonstrated significantly lower rebleeding rates (P<0.05) and reduced treatment costs (P<0.05).

Conclusion: For spontaneous large-volume intracranial hematomas treated with RA-SPD, residual volumes >15 mL achieve comparable efficacy while reducing rebleeding risk.

Keywords: robot-assisted, stereotactic, intracranial hematoma, rebleeding

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Spontaneous massive intracranial hematoma (hematoma volume ≥60 mL) can cause acute intracranial hypertensive crisis due to the space-occupying effect. It has an acute onset and a rapid progression of the disease course. Relevant studies have shown that the disability rate of patients is 68%-75%, and the mortality rate is as high as 47%-53%[1-2]. Early intervention to reduce the peak intracranial pressure, eliminate mechanical compression of hematoma, and inhibit secondary neurotoxic injury is crucial for reducing mortality and improving long-term functional independence [3]. Based on the in-depth understanding of the hematoma volume-location classification system, the efficacy of minimally invasive treatment for cerebral hemorrhage has been recognized by scholars [4-5]. Traditional guidelines for the diagnosis and treatment of cerebral hemorrhage suggest [6] that for patients with cerebral hemorrhage undergoing minimally invasive treatment, hematoma should be removed as much as possible to ensure that the residual hematoma volume at the end of treatment is ≤15ml. According to relevant reports, the postoperative rebleeding rate of patients with cerebral hemorrhage can be as high as 11%-36% (7-8]), especially for patients with preoperative hematoma volume ≥60ml (an independent risk factor for minimally invasive treatment [9]), this risk urgently requires clinical attention. Now, through the robot-assisted stereotactic puncture and drainage surgery carried out by the Neurosurgery Department of Baise People's Hospital since 2020, using

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three-dimensional reconstruction hematoma lobe modeling, robot path planning and stepped negative pressure drainage technology, the clinical efficacy of treating spontaneous massive intracranial hematoma regarding hematoma clearance volume and patient prognosis is explored, aiming to provide new ideas for the clinical prevention and treatment of massive intracranial hematoma. The technical details and clinical data are now systematically analyzed.

1. Data and Methods

1.1 General Information

A retrospective analysis was conducted on the data of 89 patients with spontaneous massive intracranial hematoma (≥60ml) admitted to our hospital from August 2022 to December 2024. According to the wishes of the patients and/or their families, they received RA-SPD treatment and were divided into the observation group: postoperative residual hematoma volume > 15ml and the control group: The postoperative residual hematoma volume is ≤15ml (postoperative residual hematoma volume = preoperative delineated hematoma volume - intraoperative aspirated hematoma volume). At admission, there were no statistically significant differences in gender, age, GCS score, NIHISS score and preoperative hematoma delineated volume between the two groups of patients ($P > 0.05$). All patients and/or their families signed the preoperative informed consent form. This study was approved by the Ethics Committee of Baise People's Hospital.

1.2 Inclusion and Exclusion Criteria

Inclusion criteria: ① Age 48 to 75 years old; ② The time from the onset of the disease to the operation was less than 24 hours; ③ The GCS score at admission was ≤12 points; ④ At admission, the volume of supragatentorial hematoma in the head CT examination was ≥60ml (combined with the Reme-Studio surgical planning system of the Remi ® neurosurgical robot, calculated through automatic segmentation using CT images). Exclusion criteria: ① Secondary cerebral hemorrhage (trauma/aneurysm/vascular malformation/Moyamoya disease/tumor); ② Failure of vital organs (heart/lung/liver/kidney); ③ Coagulation disorders, diabetes or metabolic disorders; ④ Patients who died within 30 days after the operation.

1.3 Surgical Plan

After both groups were given symptomatic treatments such as blood pressure control and fluid infusion as usual, both were treated with robot-assisted stereotactic puncture and drainage. The patients underwent tracheal intubation and general anesthesia. The supine position or healthy lateral position was selected based on the anatomical location of the hematoma. A Mayfield headframe was used for three-screw skull fixation to maintain a neutral position of the head and neck. The Reme-Studio surgical planning system of the Ruimi ® neurosurgical robot was used to import preoperative craneal CT data. Spatial registration was conducted using the robot software system (Figure 1). The hematoma area was automatically segmented through deep learning algorithms (Figure 2) to complete three-dimensional volume reconstruction and accurately quantify the hematoma volume and spatial configuration (Figure 3). According to the hematoma zoning and path planning, ellipsoidal hematoma is divided into 2-3 fan-shaped areas along the long axis, globular hematoma is divided into anterior and posterior hemispherical areas with the sagittal plane as the boundary, and irregular hematoma is divided into 2-3 subregions based on curvature analysis. Target setting: Take the geometric centers of each subregion as the puncture targets. Circumvented structures:

Integrate DTI fiber bundle imaging data to avoid the corticospinal tract, visual radiation, and important sulcus vessels, etc. Patient registration: Navigation marking balls were pasted at the reference marking points of the skull. Robotic arm registration: The degree of freedom calibration was completed using a laser tracker, and the combined registration error of the system was less than 0.5mm. The surgical area was routinely disinfected and covered with a blanket. A pointed knife was used to cut the scalp, a bone drill was used to penetrate the entire layer of the skull, and bipolar electrocoagulation was used to puncture the dura mater. Based on the planned path, a graduated silicone drainage tube was placed. After the end reached the preset target point, the tube core was removed. At the same time, a fiber optic intracranial pressure probe was placed. Stepwise decompression was initiated, gradient negative pressure aspiration was performed, and the drainage tube was opened simultaneously. Hematoma was aspirated in several sessions using a disposable sterile 5mL syringe (Figure 4). The drainage tube with lower suction resistance was aspirated first, while other drainage tubes were closed. When the suction resistance increased, the aspiration was stopped and other drainage tubes were replaced to continue the aspiration. The intraoperative hematoma aspiration volume was recorded, and the residual hematoma volume was calculated. All patients were transferred to the neurointensive care unit for treatment after the operation. Subsequently, thrombolytic mixture (5mL of normal saline + 20,000IU of urokinase) was alternately injected through each drainage tube. The drainage tubes were closed for 2 hours and then opened to promote the dissolution and discharge of the remaining hematoma. Regular head CT reexaminations were conducted to observe the clearance degree of the residual hematoma. After assessment, if the patient's vital signs are stable, the neurological risks are controllable, and the management of complications meets the standards, they can be transferred to a general ward for further treatment.

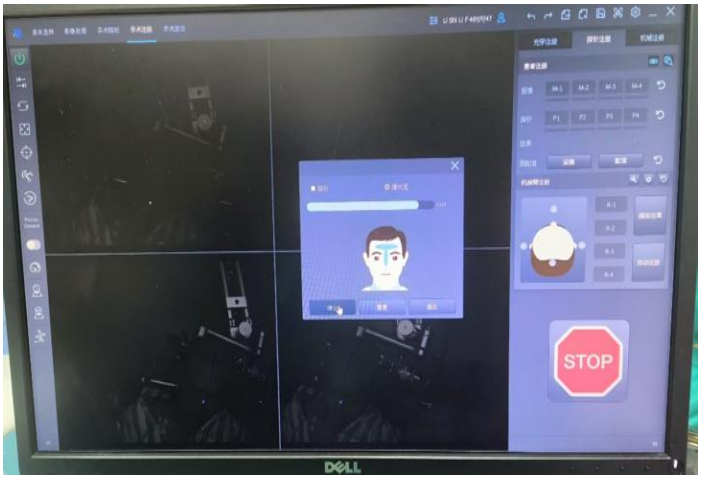
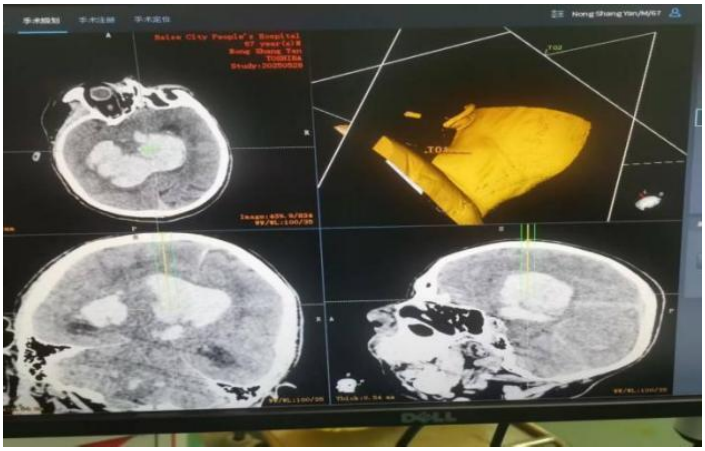
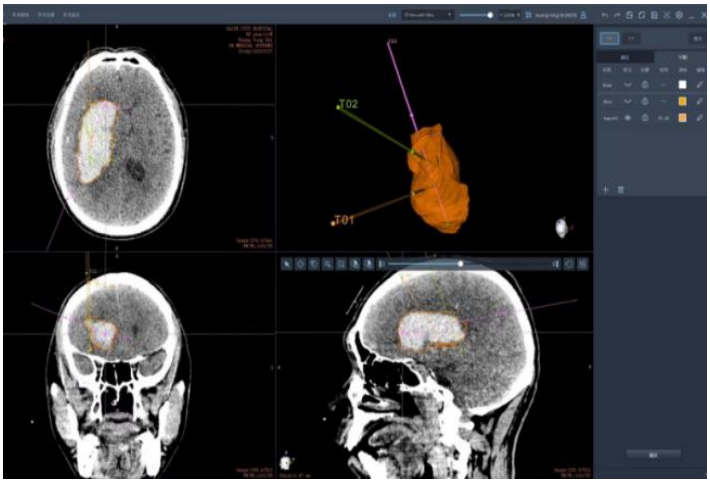


Figure 1 shows spatial registration using a robot software system. A laser pen was selected to repeatedly perform T-shaped registration verification on the patient's forehead and bridge of the nose





Figures 2- 3 depict the contour of the hematoma through automatic segmentation and reconstruct the 3D model of the hematoma

Figure 4 shows that the disposable sterile syringe (5ml) was used to aspirate hematoma respectively. The aspiration was stopped when obvious resistance was encountered

1.4 Observation Indicators

(1) General information: Gender and age of the two groups of patients, GCS score and NIHISS score at admission, delineated volume of hematoma before surgery and residual hematoma volume after surgery; (2) Prognostic data: The monitoring time in the intensive care unit, hospital stay, GCS score, NIHSS score, Barthel index score at 6 months after surgery, and the incidence of intracranial, pulmonary infection and hydrocephalus complications within 6 months after surgery in both groups of patients without rebleeding after surgery; (3) The incidence of postoperative rebleeding and treatment costs in the two groups of patients.

1.5 Statistical methods

Data processing was conducted using IBM SPSS 26.0 software, and the statistical significance was defined as $P < 0.05$. For continuous variables that conformed to normality, the mean ± standard deviation (x±s) was expressed. The t-test was used for the comparison of differences between groups, and the Wilcoxon rank sum test was performed for non-normal continuous variables. Categorical variables were expressed as frequency n and percentage (%), and chi-square test or Fisher's exact test was performed for differences between groups.

2. Result

2.1 General Information (Table 1)

Baseline data showed that the admission GCS scores of the observation group and the control group were (7.16±0.99) vs (7.02±1.17) points, and the NIHSS scores were (25.57±3.82) vs (26.42±3.43) points, respectively. The preoperative hematoma volume was (75±10) vs (74±9) mL, and the postoperative residual hematoma volume was (33±6) vs (12±1) mL. There were no statistically significant differences in the GCS score, NIHSS score and preoperative delineated hematoma volume between the two groups of patients at admission ($P>0.05$). The residual hematoma volume after the operation showed a statistically significant difference ($P<0.05$).

Table 1 Statistics of general data results of the two groups of patients

Item	Observation Group (n=49)	Control Group (n=40)	Test Statistic (t/χ^2)	P-value
Gender [Male/Female, n (%)]	25 (51.0)/24 (49.0)	28 (70.0)/12 (30.0)	χ^2=3.293	0.070
Age ($\bar{x}$±s, years)	64.78±5.37	65.85±6.27	t=-0.870	0.386
Admission GCS score ($\bar{x}$±s)	7.16±0.99	7.02±1.17	t=0.606	0.546
Admission NIHSS score ($\bar{x}$±s)	25.57±3.82	26.43±3.43	t=0.243	0.276
Preoperative hematoma volume ($\bar{x}$±s, ml)	75±10	74±9	t=0.336	0.738
Postoperative hematoma volume ($\bar{x}$±s, ml)	33±6	12±1	t=21.337	<0.01

2.1 Prognostic data (Table 2)

All patients without rebleeding after the operation were followed up for more than 6 months. Compared with the

control group, there were no statistically significant differences in the treatment time in the intensive care unit, hospital stay, GCS score at 6 months after the operation, NIHSS score, and Barthel index score in the observation group (P>0.05). Moreover, there was no statistically significant difference in the incidence of complications such as intracranial infection, pulmonary infection, and hydrocephalus within 6 months after the operation (P>0.05).

Table 2 Statistics of prognostic data results of patients without rebleeding after surgery in the two groups

Item	Observation Group (n=47)	Control Group (n=29)	Test Statistic (t/χ^2)	P-value
6-month GCS score ($\bar{X}$±s, points)	11.30±0.70	11.16±0.97	t=0.755	0.453
6-month NIHSS score ($\bar{X}$±s, points)	11.26±1.39	11.19±1.97	t=0.176	0.861
ICU stay duration ($\bar{X}$±s, days)	7.16±1.20	7.11±1.40	t=0.171	0.865
Hospital stay duration ($\bar{X}$±s, days)	32.54±7.30	33.51±6.50	t=-0.600	0.550
6-month Barthel Index ($\bar{X}$±s, points)	52.39±5.80	51.74±6.49	t=0.459	0.647
6-month complication rate (n, %)				
Intracranial infection	3 (6.4%)	1 (3.4%)	χ^2=0.310	0.578
Pulmonary infection	4 (8.5%)	2 (6.9%)	χ^2=0.064	0.800
Hydrocephalus	3 (6.4%)	2 (6.9%)	χ^2=0.008	0.930

Note: There were 2 cases of postoperative rebleeding in the observation group and 11 cases in the control group. The n value in Table 2 also changed accordingly.

2.1 Rebleeding Data (Table 2)

There were 11 cases of postoperative rebleeding in the control group and 2 cases in the observation group. The incidence of postoperative rebleeding in the observation group was lower, and the difference was statistically significant (P<0.01). The subsequent treatment cost was also lower, and the difference was statistically significant (P<0.05).

Table 3 Statistics of postoperative rebleeding results in the two groups of patients

Item	Observation Group (n=49)	Control Group (n=40)	Test Statistic (t/χ^2)	P-value
Postoperative rebleeding rate (n, %)	2 (4.1%)	11 (27.5%)	χ^2=9.683	<0.01
Hospitalization costs ($\bar{x}$±s, 10,000 CNY)	5.12±0.70	5.75±1.51	t=-2.375	0.021

Note: According to the postoperative residual hematoma volume, they were divided into the observation group (postoperative residual hematoma volume > 15ml) and the control group (postoperative residual hematoma volume ≤15ml). GCS (Glasgow Coma Scale), NIHSS (National Institutes of Health Stroke Scale), Barthel Index (Activities of Daily Living Scale) ① T-test, ② test

3. Discussion

Spontaneous massive intracranial hematoma (hematoma volume ≥60ml) can lead to acute and severe intracranial pressure increase [10-11], with an acute mortality rate of approximately 50%[12]. On the one hand, the local compression effect caused by massive intracranial hematoma can cause physical damage to the surrounding brain tissue. On the other hand, secondary high intracranial pressure and low perfusion can induce cerebral edema and

hypoxia of brain cells. It leads to a series of problems such as calcium ion overload, free radical generation, and toxic effects of excitatory amino acids, intensifying the degree of neurological function impairment [13]. Meanwhile, uncleared hematoma may block the cerebrospinal fluid circulation pathway, promoting the deterioration of cerebral edema. Moreover, the neurotoxic substances released by the lysis of red blood cells will further damage the brain tissue, leading to progressive impairment of neurological function. Therefore, early and effective removal of intracranial hematoma to alleviate mechanical compression and secondary brain injury is of decisive significance for improving the prognosis of patients [14-15].

During the process of hematoma evacuation for massive cerebral hemorrhage, whether postoperative rebleeding can be avoided is a key factor determining the success of the surgery [16], and the causes of postoperative rebleeding have always been one of the core difficulties in clinical treatment [17]. Excluding the influence of differences in individual factors of patients (such as coagulation dysfunction and underlying diseases like diabetes), combined with clinical data and literature analysis [18], The emergence of this difficult problem has a significant pathological association with the "Normal Perfusion Pressure Breakthrough Theory (NPPB)". This clinical phenomenon is manifested as follows: When large-volume intracranial space-occupying lesions (such as hematoma, tumor, malformed vascular mass, etc.) are surgically removed, secondary cerebral hemorrhage of unknown cause often occurs after the operation. Spetzler et al. [19] first defined such pathological processes as "Normal Perfusion Pressure Breakthrough" (NPPB). Based on this theory, the mechanism of postoperative rebleeding in patients with massive intracranial hemorrhage can be explained from the following two aspects: 1) Hemodynamic mechanism: The space-occupying effect caused by massive intracranial hematoma induces chronic ischemia and hypoxia in the surrounding brain tissue, resulting in continuous compensatory dilation of the feeding arteries and progressive loss of the function of autonomous blood flow regulation. If the amount of hematoma clearance during the operation is too large, sudden reperfusion will occur in the lesion area. However, the autoregulation ability of the blood vessels has not been reconstructed [20], and it is unable to buffer the sharp increase in perfusion pressure, eventually causing vascular rupture hemorrhage [21]. 2) Mechanical injury mechanism: The cavities formed after the clearance of a large number of intracerebral hematomas cause the displacement and collapse of adjacent brain tissues. Microvessels suffer structural damage due to mechanical traction injury and then rupture and bleed [21-22]. The release of the space-occupying effect triggered hemodynamic changes, and the formation of the collapse effect led to mechanical microvascular injury. Both formed the main causes of postoperative rebleeding [23]. A similar principle was also involved in another randomized trial [24]. The results of a meta-analysis conducted by Jiang Xiaobing et al. Indicated that For patients with cerebral hemorrhage volume ≥60 mL, such patients have a dangerous onset and rapid disease changes. With the sharp fluctuation of intracranial pressure gradient after hematoma clearance, the risk of postoperative rebleeding is significantly increased [25]; It can be seen from this that for patients with massive cerebral hemorrhage, the control of the amount of hematoma removed during the operation is particularly important. It is necessary to not only remove the hematoma but also minimize secondary brain injury to the greatest

extent, thereby improving the prognosis of the patients.

Minimally invasive treatment requires controlling the residual hematoma volume to less than 15ml [6]. However, in 2024, a multicenter randomized controlled trial conducted by Professor Chen Xiaolei's team from the General Hospital of the People's Liberation Army of China pointed out that in the process of stereotactic minimally invasive treatment for sutent hematoma patients, the hematoma clearance rate and prognosis improvement were threshold-dependent, that is, within a certain range, increasing the clearance rate could improve prognosis. However, the marginal benefit of continued clearance after exceeding the critical value is significantly reduced; The results of the subgroup analysis based on whether the residual hematoma volume in the trial was greater than 15 ml showed that some patients could still achieve good clinical efficacy even if the postoperative residual hematoma volume was > 15 ml [26]. Furthermore, a retrospective study of 413 patients with supratentorial hematoma found that for patients with severe deterioration of the condition, stereotactic minimally invasive treatment was performed. During the operation, only about half of the hematoma volume needed to be aspirated, and the remaining hematoma volume was discharged through a catheter by intracavitary injection of urokinase. This method can solve the drawback of postoperative rebleeding to a certain extent [27].

Precision treatment and minimally invasive treatment are currently the two major development trends in the field of neurosurgery for the treatment of cerebral hemorrhage. Robot-assisted stereotactic puncture and drainage (RA-SPD) has become a key clinical approach for the treatment of cerebral hemorrhage due to its advantages such as minimally invasive characteristics, technical accessibility and rapid postoperative recovery [28]. In view of the analysis results of the clinical data of the two groups of patients, this trial concluded that RA-SPD for the treatment of spontaneous massive intracranial hematoma has the following two major characteristics regarding the relationship between hematoma clearance volume and the prognosis of patients: ① According to the specific morphology and zoning of the hematoma, the surgical approach was planned. Drainage tubes were precisely inserted respectively, and aspiration was performed separately in multiple zones. When the intracranial pressure monitoring value has dropped to the normal range, even if the residual hematoma volume is > 15ml, thrombolytic mixture (5mL of normal saline + 20,000IU of urokinase) was alternately injected through each drainage tube after the operation to promote the dissolution and discharge of the remaining hematoma. The stepwise regulation of intracranial pressure was achieved, and good therapeutic effects could still be obtained compared with the control group. ② Based on the core viewpoint of the NBBP theory, compared with the control group, the observation group did not perform large-volume hematoma evacuation during the operation. To a certain extent, it gave time to the lesion vessels around the hematoma, increased the tolerance threshold of the vessels to reperfusion blood flow, weakened the microvascular mechanical injury induced by the collapse effect, significantly reduced the risk of postoperative rebleeding, and avoided the second-stage hematoma evacuation surgery. While reducing medical costs, it also alleviates the load on the medical insurance system and the economic pressure of patients' out-of-pocket expenses.

4. Summary

In conclusion, for patients with spontaneous massive intracranial hematoma, during the process of hematoma evacuation using robot-assisted stereotactic puncture and drainage, the monitoring of intracranial pressure should be the surgical endpoint, that is, the main focus should be on reducing intracranial pressure, but it is not necessary to remove the hematoma to less than 15ml as much as possible. According to the results of this trial, even if the residual hematoma volume after the operation is greater than 15ml, It can still achieve good clinical efficacy and reduce the risk of postoperative rebleeding.

This study has limitations such as a small sample size and a retrospective design. Moreover, the optimal treatment timing of RA-SPD for massive cerebral hemorrhage remains controversial, which may have a certain impact on the results. In addition, due to the 6-month short-term follow-up, the assessment of long-term prognosis still needs to expand the observation period. It is still necessary to carry out targeted large-sample, surgical timing, prospective multicenter randomized controlled trials. Based on the hematoma evacuation threshold, to further explore the clinical efficacy of robot-assisted stereotactic puncture and drainage in the treatment of spontaneous massive intracranial hematoma.

Conflict of Interests

None.

Conflict of funding statement

None.

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