scientific reports

Check for updates

OPEN

Characteristics, predictors and outcomes of early postoperative cerebral infarction on computed tomography in spontaneous intracerebral hemorrhage

Kun Lin[1,2,4], Chuang Gao[3,4], Zhicheng Lin[2], Yinhai Tang[2], Yuanxiang Lin[1]✉ & Rongcai Jiang[3]✉

Early postoperative cerebral infarction (ePCI) is a serious complication of spontaneous intracerebral hemorrhage (SICH). Yet, no study has specifically focused on ePCI among SICH patients. Our study aims to investigate the characteristics, predictors, and outcomes of ePCI observed on computed tomography (CT) within 72 h after surgery in patients with supratentorial SICH. Data from a single-center SICH study conducted from May 2015 to September 2022 were retrospectively analyzed. We described the characteristics of ePCI. Predictors were identified through logistic regression analysis, and the impact of ePCI on six-month mortality was examined using a Cox regression model. Subgroup analyses and the "E-value" approach assessed the robustness of the association between ePCI and mortality. A retrospective analysis of 637 out of 3938 SICH patients found that 71 cases (11.1%) developed ePCI. The majority of ePCI cases occurred on the bleeding side (40/71, 56.3%) and affected the middle cerebral artery (MCA) territory (45/71, 63.4%). Multivariable analysis showed that the Glasgow Coma Scale (GCS) score (odds ratio (OR), 0.62; 95% CI, 0.48–0.8; p < 0.001), bleeding volume (per 100 ml) (OR, 1.17; 95% CI, 1.03–1.32; p = 0.016), hematoma volume (per 10 ml) (OR, 1.14; 95%CI, 1.02–1.28; p = 0.023) and bilateral brain hernia (OR, 6.48; 95%CI, 1.71–24.48; p = 0.006) independently predicted ePCI occurrence. ePCI was significantly associated with increased mortality (adjusted hazard ratio (HR), 3.6; 95% CI, 2.2—5.88; p < 0.001). Subgroup analysis and E-value analysis (3.82—6.66) confirmed the stability of the association. ePCI is a common complication of SICH and can be predicted by low GCS score, significant bleeding, large hematoma volume, and brain hernia. Given its significant increase in mortality, ePCI should be explored in future studies.

Keywords Surgery, Intracerebral hemorrhage, Cerebral infarction, Prognosis, Complication

Spontaneous intracerebral hemorrhage (SICH) is a highly destructive disease with higher mortality and disability rates compared to ischemic stroke[1]. Despite substantial advances in treatment, SICH prognosis shows little improvement. The 30-day mortality rates are high, ranging from 35 to 52%, with merely about 20% achieving functional independence at 6 months[2]. Theoretically, surgical interventions can alleviate the mass effect, rapidly lower elevated intracranial pressure (ICP), enhance cerebral blood flow, and mitigate hematoma-induced cytotoxic reactions, potentially improving patient prognosis. Nevertheless, the conclusive advantage of surgical interventions, including craniotomy, endoscopic surgery, and minimal puncture drainage[3–7], is still unclear.

Currently, many studies focus on hemorrhagic transformation after cerebral infarction as a main factor contributing to poor prognosis[8]. However, only a few studies have explored cerebral infarction complications in

[1]Department of Neurosurgery, The First Affiliated Hospital, Fujian Medical University, 20 Chazhong Road, Fuzhou 350005, China. [2]Department of Neurosurgery, Fujian Medical University Provincial Clinical Medical College, 516 Jinrong South Road, Fuzhou 350028, China. [3]Department of Neurosurgery, Tianjin Medical University General Hospital, 154 Anshan Road, Tianjin 300052, China. [4]These authors contributed equally: Kun Lin and Chuang Gao. ✉email: lyx99070@163.com; jiang116216@163.com

SICH. Recently, high rates of diffusion-restricted lesions on diffusion-weighted imaging (DWI) consistent with cerebral infarcts (11.1–41%) have been described in minor or moderate SICH patients[9]. These lesions are often small and associated with poor outcomes[10]. Given that severe SICH often necessitates surgical intervention, and the natural process of cerebral infarction complication in severe SICH is rarely observed, we focus on early postoperative cerebral infarction (ePCI) in such SICH patients. ePCI is a serious complication of SICH and may partly explain the difficulty in improving the outcomes through surgery. To the best of our knowledge, no study has specifically focused on ePCI in patients with SICH. In this study, we aimed to investigate the incidence and distribution of ePCI seen on computed tomography (CT), its predictors, and its association with six-month mortality in supratentorial SICH patients by retrospectively analyzing data from a large, single-center study of SICH.

Methods

Study design and participants

This is a retrospective cohort study and follows the Strengthening the Reporting of Observational Studies in Epidemiology guidelines. All SICH patients admitted to the Shengli Clinical Medical College of Fujian Medical University from May 2015 to September 2022 were enrolled. Inclusion criteria were: SICH involving the basal ganglia, lobar, or thalamic regions; Age ≥ 18 years; undergoing surgical treatment; follow-up period ≥ 6 months. Exclusion criteria included: hemorrhage due to trauma, intracranial tumors, aneurysms, arteriovenous malformations, arteriovenous fistulas, infarction, or other lesions; coagulation dysfunction from hereditary coagulopathy, cancer, liver or kidney dysfunction; infratentorial cerebellar or brainstem hemorrhage; primary ventricular hemorrhage; age < 18 years; absence of surgical treatment; incomplete follow-up; history of severe stroke, heart, lung, liver, or kidney diseases; cerebral infarction occurring before surgery or more than 72 h after surgery; and postoperative cerebral infarction directly caused by surgical procedures. Surgical indications, aligned with our prior reports[11], included transtentorial herniation, supratentorial hematoma > 30 ml, midline shift > 1 cm, and obstructive hydrocephalus. At our center, the perioperative management of antiplatelet/anticoagulant agents involves immediate discontinuation upon the detection of intracerebral hemorrhage, with resumption of the therapy more than two weeks after surgery.

Data collection

Trained study staff collected demographic data and medical histories, including hypertension, diabetes, prior ischemic/hemorrhagic stroke, coronary heart disease, deep vein thrombosis, atrial fibrillation, and consumption of antiplatelet/anticoagulant medications, by reviewing electronic medical records, as previously described[11]. Clinical parameters before surgery, such as Glasgow Coma Scale (GCS), original intracerebral hemorrhage scale (OICH), modified intracerebral hemorrhage A score (MICH-A)[12], and signs of cerebral herniation, were also retrieved. Surgical parameters, such as approach, time from ictus to surgery, duration of surgery, and intraoperative blood loss, were recorded. Clinical data on postoperative complications (infectious meningitis, pulmonary infection, epilepsy), as well as intensive care unit (ICU) and hospital stay lengths, were also collected. Surgical approaches included open surgery (decompressive craniectomy with hematoma evacuation, craniotomy microsurgery) and minimally invasive surgery (endoscopic surgery, minimal puncture drainage, and simple extra ventricular drainage (EVD)). Pneumonia, infectious meningitis[13], and epilepsy[14] were diagnosed according to established guidelines.

We determined hematoma lateralization, hematoma location, hematoma volume, presence of intraventricular hemorrhage, Graeb, s scores, postoperative hematoma volume, rebleeding, and hematoma evacuation rate (%) on brain CT scans obtained within 24 h before surgery and within 24 h after surgery according to previously validated methodology[11]. Hematoma locations, including lobar, thalamus, and basal ganglia, were dichotomized into lobe and deep (thalamus and basal ganglia). Neuroimaging was analyzed blindly, without clinical information.

Early postoperative cerebral infarction (ePCI) definition

ePCI was defined as a new identifiable low-density lesion in the non-surgical areas observed on CT within 72 h after surgery, similar to previous reports[15,16]. The mere presence of newly added low-density regions in the surgical area was indicative of postoperative edema or surgical tissue injury, rather than cerebral infarction (Supplementary Fig. 1a,b). Lesions aligning with damaged cerebral arteries during surgery were defined as ePCI directly caused by surgical procedures (Supplementary Fig. 1c,d). New low-density lesions in non-surgical areas, apart from those directly caused by the surgical procedures, were defined as ePCI not directly caused by surgical procedures (Supplementary Fig. 1e,f). Cases with both types of ePCI were classified under ePCI not directly caused by surgical procedures (Supplementary Fig. 1g,h). ePCI territories were documented based on vascular regions: anterior cerebral artery (ACA), middle cerebral artery (MCA), posterior cerebral artery (PCA), vertebrobasilar (VB), and anterior choroidal artery (AChA) territories. ePCI lateralization was categorized as ipsilateral, contralateral, or bilateral.

Follow up data

Follow-up was conducted by independent, clinically data-blinded study staff through outpatient visits, telephone interviews, or WeChat communications. The primary outcome was mortality at 6 months. Secondary outcomes included functional outcomes at 6 months, lengths of ICU and hospital stay, and postoperative complications such as infectious meningitis, pulmonary infection, epilepsy, and rebleeding. Neurological functional status at 6 months was evaluated using the Extended Glasgow Outcome Scale (GOS-E), categorizing results into favorable (GOS-E score, 5–8) and unfavorable (GOS-E score, 1–4).

Statistical methods

Baseline characteristics were categorized by ePCI or no postoperative cerebral infarction (nPCI). Continuous and categorical variables were reported as mean ± standard deviation (SD) or median (interquartile range, IQR), and counts (percentages), respectively. Normality was assessed using the Shapiro–Wilk test, and t-tests or Mann–Whitney U-tests were used for intergroup comparisons depending on variable distribution. Categorical variables were compared using the chi-square tests or Fisher's exact probability tests. Fisher`s exact probability test was used when the theoretical frequency less than 5.

Logistic regression models were used to investigate each risk factor. In the univariable analysis, variables with $p < 0.1$ were selected for multivariable logistic regression analysis in a backward stepwise model. Before entering candidate predictors into the multivariable analysis, multicollinearity was assessed using variance inflation factors (VIFs).

Cox regression analysis evaluated the ePCI-mortality relationship, calculating hazard ratios (HRs) and 95% confidence intervals (CIs). Multivariable models were built, cumulatively adjusting for confounders such as age, gender (Model 1), diabetes, hypertension (Model 2), GCS score, bleeding location (Model 3), preoperative hematoma volume, brain herniation presence, Graeb's score (Model 4), OICH, and MICH-A (Model 5). Selection of confounding factors was guided by their clinical significance. Kaplan–Meier curves for mortality, based on ePCI or nPCI status, were generated and compared using the log-rank test. To assess result robustness, subgroup analyses were also conducted for different patient groups, such as gender, age (< 60 years, ≥ 60 years), hypertension status, diabetes status, bleeding location (lobe, deep), and ventricular hemorrhage status. Interaction terms were added to the adjusted model to evaluate potential interactions. E-values were calculated to explore the impact of unmeasured confounders on the robustness of the association between ePCI and mortality.

All analyses were conducted using R version 4.2.2 (R Foundation for Statistical Computing) (http://www.R-project.org, The R Foundation) and the Free Statistics analysis platform. Two-sided tests were used, with a significance threshold set at $p < 0.05$.

Ethical approval

The study was approved by the Institutional Review Board of Fujian Provincial Hospital, Fujian Medical University (K2022-11-004), and was registered in the Chinese Clinical Trial Registry (ChiCTR2300074977). Due to the retrospective cohort study design, the requirement to obtain informed consent was waived by the Institutional Review Board.

Results

Study participants

During the study enrollment period, 3968 consecutive SICH patients were admitted to Fujian Medical University Provincial Clinical Medical College. Of these, 843 patients (21.2%) underwent surgery. Following the inclusion and exclusion criteria, 637 patients (454 males, 71.3%), with a mean age of 57.3 ± 12.5 years, were included in the analysis. Patient selection is illustrated in flowchart Fig. 1. Baseline characteristics of the study cohort are described in Table 1.

Incidence, distribution and predictors of ePCI

In our cohort, the incidence of ePCI was 11.1% (71/637). Of these, ePCI was present on the bleeding side in 40 cases (56.3%), the opposite side in 5 cases (7.0%), and bilaterally in 26 cases (36.6%). The MCA territory was the most common site for ePCI (63.4%, 45/71). ePCI also occurred in the PCA territory (28 cases, 39.4%), ACA territory (18 cases, 25.4%), VB territory (10 cases, 14.1%), and AChA territory (8 cases, 11.3%). The lesions were confined to one vascular territory in 40 cases and to multiple territories in 31 cases.

The results of univariable analyses of ePCI predictors are presented in Supplementary Table 1. Candidate predictors for multivariable analysis, selected based on a p-value < 0.10, included hypertension, history of antiplatelet/anticoagulation medication use, GCS, Graeb score, brain herniation status, surgical method, operation time, bleeding volume (per 100 ml), history of myocardial infarction, atrial fibrillation, and hematoma volume (per 10 ml). OICH and MICH-A were not included in the model because of their severe multicollinearity (VIF > 5). Following backward-stepwise selection, independent predictors of ePCI were identified as GCS (OR 0.62, 95%CI 0.48–0.80, $p < 0.001$), bleeding volume (per 100 ml) (OR 1.17, 95%CI 1.03–1.32, $p = 0.016$), hematoma volume (per 10 ml) (OR 1.14, 95%CI 1.02–1.28, $p = 0.023$) and bilateral brain herniation (OR 6.48, 95%CI 1.71–24.48, $p = 0.006$) (Table 2).

ePCI associated with mortality

In the unadjusted model, ePCI was significantly associated with an increased risk of six-month mortality (HR 5.87; 95% CI 4.05–8.52; $p < 0.001$). Extended multivariable models consistently revealed significant HRs for ePCI across all five models (HRs ranged 3.30–5.97, $p < 0.001$ for all; see Table 3 for details). Subgroup analysis did not show any significant interactions (Fig. 2). Kaplan–Meier survival curves also showed higher six-month mortality in ePCI (log-rank test: $p < 0.001$, Fig. 3). The E-value for the association between ePCI and six-month mortality ranged from 3.82 to 6.66.

Secondary outcome analysis

The proportion of favorable clinical outcomes (GOSE 5–8) at 6 months in the ePCI group was merely 4.2% (3/71), significantly lower than in the nPCI group (49.6%, 281/566) ($p < 0.001$). The distribution of GOSE scores at 6 months for both the ePCI and nPCI groups is shown in Supplementary Fig. 2. Other secondary outcomes indicated that ePCI did not increase the risk of postoperative infectious meningitis, pulmonary infection, epilepsy,

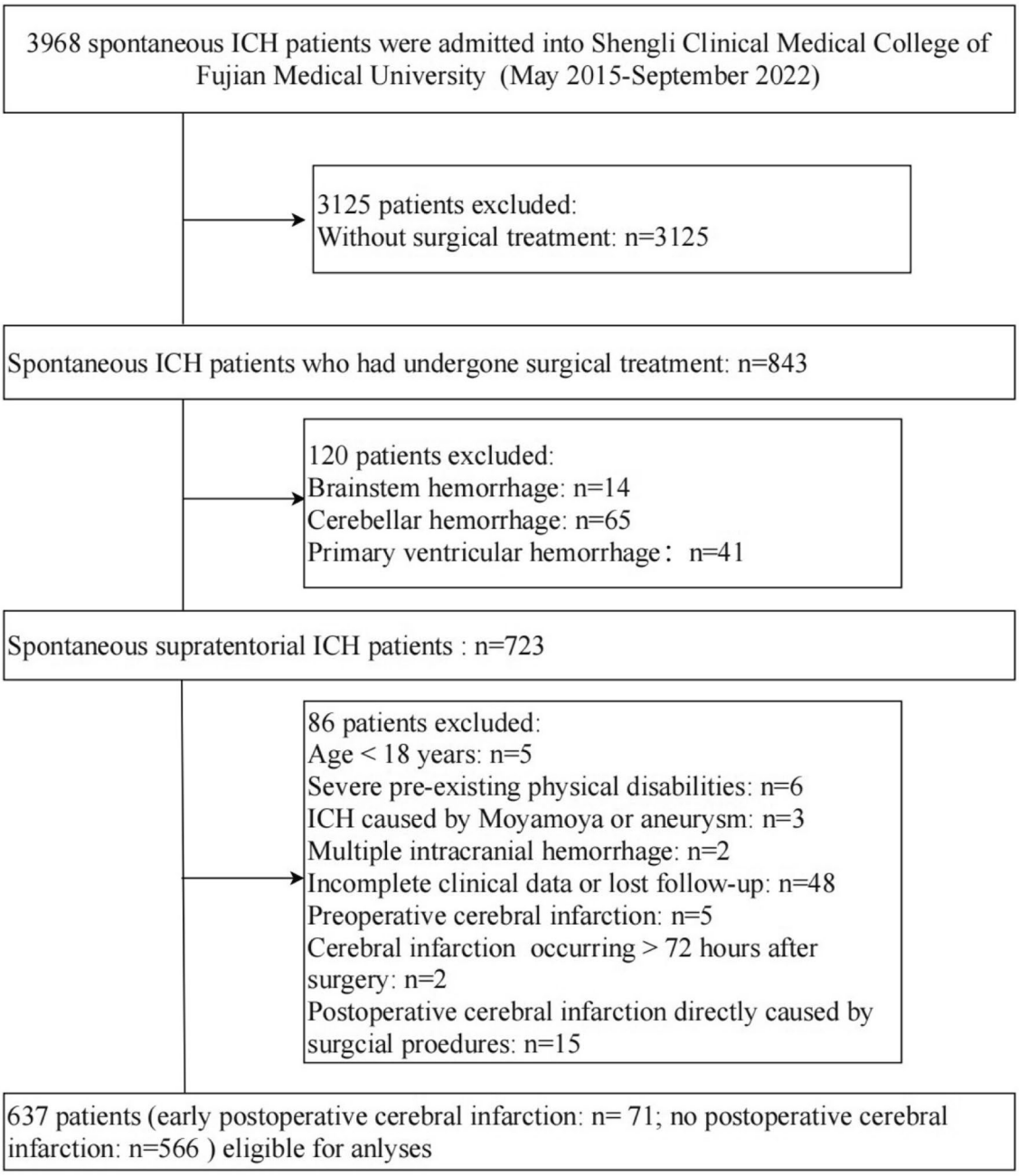

Figure 1. Flowchart for selection of cases in study. ICH, intracerebral hemorrhage.

or rebleeding. It also did not contribute to an increase in the length of hospital stay. However, ePCI significantly prolonged ICU stay duration (see Supplementary Table 2).

Discussion

Our study revealed that ePCI seen on CT within 72 h after surgery (1) occurred in 11.1% of SICH patients, (2) predominantly affected the bleeding side and the MCA territory, (3) was predicted by GCS score, bleeding volume, hematoma volume, and brain herniation, and (4) was associated with higher postoperative 6 month mortality.

In our cohort, ePCI frequently occurred at the bleeding site, potentially due to the more severe compression of ipsilateral blood vessels. Unlike posttraumatic cerebral infarction (PTCI), typically located in the PCA territory[17–19], ePCI in supratentorial SICH primarily occurred in the MCA territory in our study. This distinction may stem from PTCI often being caused by transtentorial herniation due to subdural or epidural hematomas compressing the PCA[17–19]. Conversely, SICH predominantly occurs in the basal ganglia or thalamic regions, exerting a significant mass effect on the MCA. Furthermore, the trans-sylvian surgical approach to SICH may increase the likelihood of ePCI in the MCA territory due to surgical disruptions.

Variables	Total (n = 637)	nPCI (n = 566)	ePCI (n = 71)	*P* value
Male, n (%)	454 (71.3)	402 (71)	52 (73.2)	0.697
Age[a], years	57.3 ± 12.5	57.3 ± 12.5	57.4 ± 12.6	0.951
Age group, < 60 years, n (%)	367 (57.6)	326 (57.6)	41 (57.7)	0.981
Hypertension, n (%)	499 (78.3)	449 (79.3)	50 (70.4)	0.086
Diabetes, n (%)	120 (18.8)	107 (18.9)	13 (18.3)	0.904
Antiplatelet/Anticoagulation, n (%)	37 (5.8)	27 (4.8)	10 (14.1)	0.005
GCS[b]	7.0 (7.0, 12.0)	7.0 (7.0, 13.0)	4.0 (3.0, 5.5)	< 0.001
Hematoma volume[b], ml	40.5 (27.2, 60.8)	38.4 (26.2, 57.1)	66.6 (57.1, 80.0)	< 0.001
Side, left, n (%)	335 (52.6)	296 (52.3)	39 (54.9)	0.675
Location, n (%)				0.023
Basal ganglia	375 (58.9)	330 (58.3)	45 (63.4)	
Thalamus	95 (14.9)	92 (16.3)	3 (4.2)	
Lobe	167 (26.2)	144 (25.4)	23 (32.4)	
Location group, deep, n (%)	470 (73.8)	422 (74.6)	48 (67.6)	0.209
Ventricular hemorrhage, n (%)	380 (59.7)	332 (58.7)	48 (67.6)	0.147
Graeb[b]	1.0 (0.0, 4.0)	1.0 (0.0, 4.0)	2.0 (0.0, 5.0)	0.088
Minimal depth from cortical surface[a], mm	15.2 ± 10.5	15.8 ± 10.8	10.8 ± 6.6	< 0.001
Transtentorial herniation, n (%)				< 0.001
No	426 (66.9)	419 (74)	7 (9.9)	
Unilateral hernia	146 (22.9)	122 (21.6)	24 (33.8)	
Bilateral hernia	65 (10.2)	25 (4.4)	40 (56.3)	
Surgical method, n (%)				< 0.001
Simple extra ventricular drainage	64 (10.0)	63 (11.1)	1 (1.4)	
Open surgery	369 (57.9)	307 (54.2)	62 (87.3)	
Small bone window	101 (15.9)	100 (17.7)	1 (1.4)	
Endoscopic surgery	90 (14.1)	84 (14.8)	6 (8.5)	
Puncture drainage	13 (2.0)	12 (2.1)	1 (1.4)	
Time to operation[a], hours	43.7 ± 65.3	46.6 ± 66.7	20.6 ± 46.5	< 0.001
Operation time[a], minutes	154.8 ± 68.8	150.5 ± 68.6	188.7 ± 61.6	< 0.001
Bleeding[a], ml	225.8 ± 212.4	204.7 ± 189.9	394.4 ± 294.3	< 0.001
Cerebral infarction history, n (%)	25 (3.9)	21 (3.7)	4 (5.6)	0.51
Cerebral hemorrhage history, n (%)	24 (3.8)	23 (4.1)	1 (1.4)	0.503
Coronary heart disease, n (%)	22 (3.5)	17 (3)	5 (7)	0.087
Deep venous thrombosis history, n (%)	4 (0.6)	3 (0.5)	1 (1.4)	0.377
Atrial fibrillation, n (%)	25 (3.9)	18 (3.2)	7 (9.9)	0.015
OICH[b]	2.0 (2.0, 3.0)	2.0 (2.0, 3.0)	3.0 (3.0, 4.0)	< 0.001
MICH-A[b]	5.0 (3.0, 6.0)	5.0 (3.0, 6.0)	7.0 (6.0, 8.0)	< 0.001
Postoperative hematoma[b], ml,	4.5 (1.5, 11.2)	4.3 (1.3, 10.4)	5.5 (2.8, 14.1)	0.281
Clearance rate[b], %,	90.1 (68.1, 96.8)	89.8 (66.3, 97.0)	91.3 (80.2, 96.4)	0.449

Table 1. Baseline characteristics of participants. *nPCI* no postoperative cerebral infarction, *ePCI* early postoperative cerebral infarction, *OICH* original intracerebral hemorrhage scale, *MICH-A* modified intracerebral hemorrhage A score. [a]Values are mean ± standard deviation (SD). [b]Values are median (interquartile range).

Variables	Odds ratio (95% CI)	*P* value
GCS	0.62 (0.48–0.80)	< 0.001
Bleeding (per 100 ml)	1.17 (1.03–1.32)	0.016
Hematoma volume (per 10 ml)	1.14 (1.02–1.28)	0.023
Transtentorial herniation		
No	1.00 (ref)	
Unilateral hernia	2.39 (0.86–6.63)	0.093
Bilateral hernia	6.48 (1.71–24.48)	0.006

Table 2. Multivariable model of independent predictors of early postoperative cerebral infarction. *CI* confidence interval, *GCS* glasgow coma scale.

	Unadjusted	Model 1	Model 2	Model 3	Model 4	Model 5
HR (95% CI)	5.87 (4.05–8.52)	5.08 (3.6–7.18)	5.97 (4.11–8.68)	3.47 (2.22–5.42)	3.3 (2.05–5.31)	3.6 (2.2–5.88)
P value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table 3. Cox Regression for ePCI on 6 month Mortality. Model 1 = adjusted for age + gender. Model 2 = Model 1 + (diabetes + hypertension). Model 3 = Model 2 + (GCS + location). Model 4 = Model 3 + (preoperative hematoma volume + hernia + graeb). Model 5 = Model.4 + (OICH + MICH-A). *HR* hazard ratio, *CI* confidence interval, *ePCI* early postoperative cerebral infarction, *OICH* original intracerebral hemorrhage scale, *MICH-A* modified intracerebral hemorrhage, *GCS* Glasgow Coma Scale.

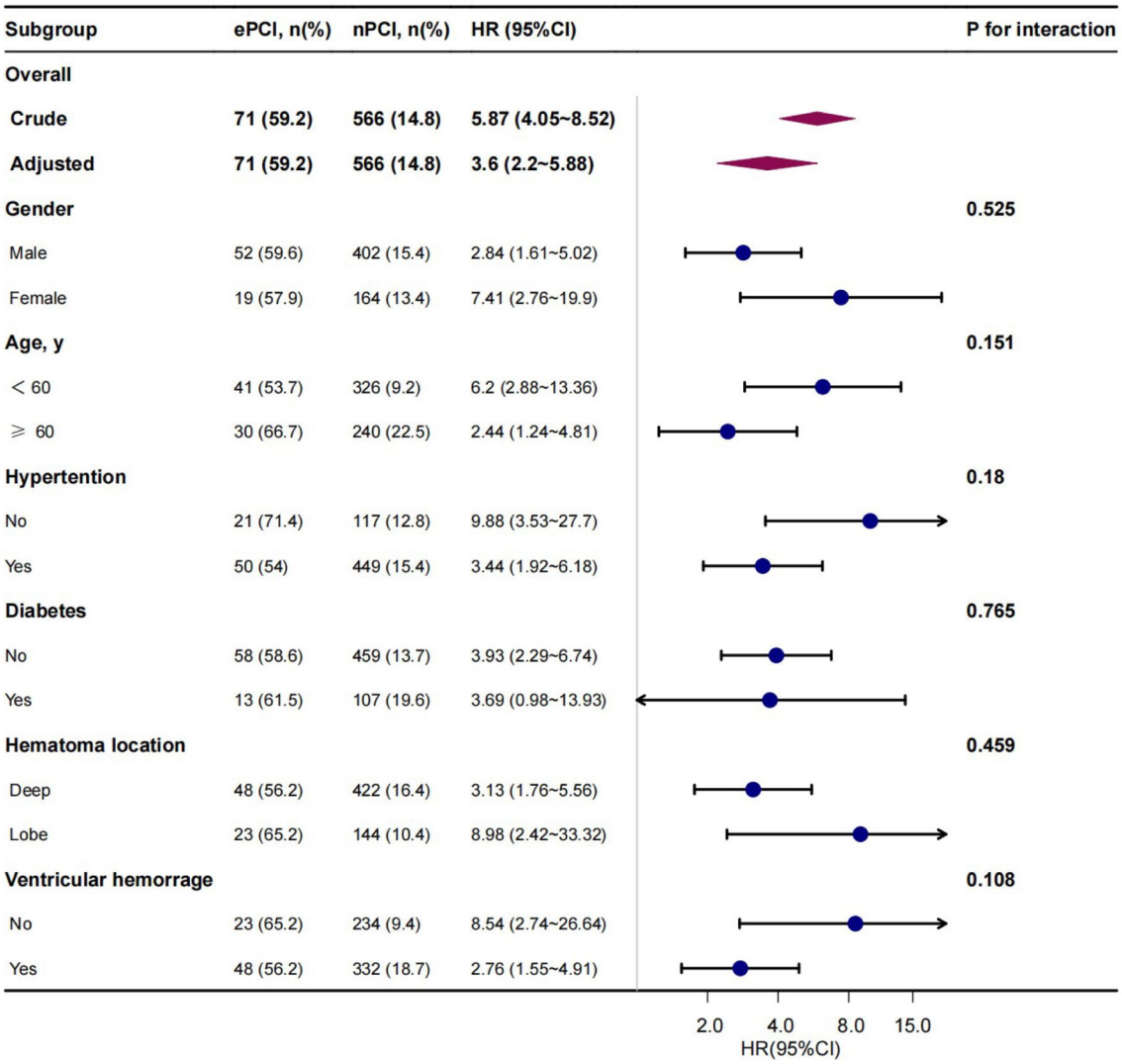

Figure 2. Stratified multivariable analysis of the association between early postoperative cerebral infarction and 6-month mortality. ePCI, early postoperative cerebral infarction; nPCI, no postoperative cerebral infarction.

Low GCS, large hematoma volume, and brain herniation, closely associated with SICH severity[20,21], emerged as independent risk factors for ePCI, underscoring that the more severe the condition, the higher the incidence of ePCI. Hence, we speculate that the primary pathophysiological mechanisms behind ePCI appear to involve elevated ICP reducing cerebral perfusion pressure and blood flow, alongside mechanical compression and occlusion of intracranial vessels by the mass effect of the hematoma. In brain herniation, compression of the intracranial artery by displaced brain tissue can cause infarction. These findings indicate that immediate surgical intervention to lower ICP and alleviate vascular compression is essential in reducing ePCI in severe SICH cases.

Our study also identified intraoperative bleeding as an independent predictor for ePCI. Significant intraoperative bleeding may lead to hypotension and hypoperfusion, inducing ischemic brain injury. While our univariable analysis identified preoperative antiplatelet/anticoagulant therapy (with perioperative cessation) as a risk factor for ePCI, the multivariable analysis did not demonstrate statistical significance. Nonetheless, caution is advised

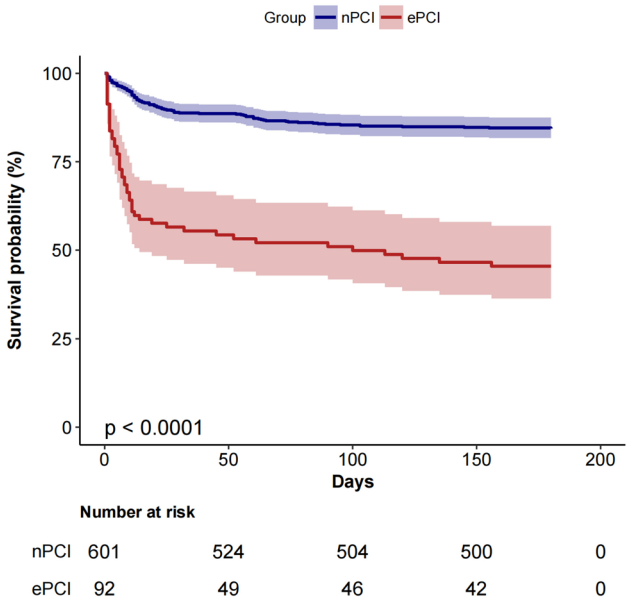

Figure 3. Kaplan–Meier survival curves for days 180 of spontaneous supratentorial intracerebral hemorrhage with early postoperative cerebral infarction. The shaded areas in the Kaplan–Meier curves represent 95% confidence intervals. ePCI, early postoperative cerebral infarction; nPCI, no postoperative cerebral infarction.

in interpreting these results due to potential patient selection biases and the lack of detailed disease stratification. Notably, patients on preoperative antiplatelet or anticoagulant therapy may be more inclined to refuse surgery, given a higher likelihood of adverse outcomes.

Univariable analysis suggested minimally invasive surgery could potentially reduce ePCI incidence, yet multivariable analysis did not confirm this difference as statistically significant. This may reflect a bias wherein patients with more severe conditions, often selected for open surgery, inherently possess a higher risk of ePCI. Unexpectedly, our study did not find an increase in ePCI among patients with a history of certain conditions, such as cerebral infarction, ICH, or myocardial infarction. At present, this outcome remains unexplained. Of note, patients with a history of severe cerebral infarction or ICH were not included in the study. Literature indicates that 11.1–41% of minor or moderate ICH patients show remote diffusion-restricted infarct lesions on DWI, potentially due to microangiopathy[9]. Further research is needed to ascertain whether microangiopathy is responsible for ePCI seen on CT after severe ICH. Another potential mechanism of ePCI is vasospasm, which frequently occurs in cases of subarachnoid hemorrhage and intraventricular hemorrhage[22–24]. Our data indicate that the ePCI group exhibited a higher proportion of intraventricular hemorrhage and elevated Graeb scores; however, these differences did not achieve statistical significance. The relationship between vasospasm and ePCI warrants further investigation.

Similar to previous reports on PTCI in traumatic brain injury and early cerebral infarction following aneurysmal subarachnoid hemorrhage[16–19,25,26], our data showed a strong association between ePCI after SICH and poorer clinical outcomes, as well as higher six-month mortality, attributable to several factors. First, the acute phase of SICH renders brain tissue fragile, increasing vulnerability to secondary ischemic damage. Second, the predominance of ePCI in the functional areas of MCA territory exacerbates the negative impact on prognosis. Third, currently, no effective treatment is available for ePCI after SICH. Although intravenous thrombolysis (IVT) and mechanical thrombectomy (MT) are established treatments for acute ischemic stroke[27,28], IVT is contraindicated in ePCI cases due to bleeding risks. MT may be a potential treatment option for ePCI after SICH, with favorable outcomes in cases of SICH complicated by acute large vessel occlusion reported in literature[29]. The etiology of ePCI after SICH is multifactorial, including vascular compression, reduced cerebral perfusion, surgery-related damage, and cerebral thrombus formation. Identifying thrombotic infarction within the time window for MT after SICH is challenging, as patients are often in a comatose or sedated state postoperatively. Our study suggests ePCI is a cornerstone complication of ICH and may partly explain why it seems so difficult to improve the outcome by surgery. In instances where ePCI is inevitable, surgical intervention should be approached with caution.

Our study has several strengths. This is the first study in severe ICH patients with surgery reporting on incidence, distribution, predictors, and outcomes of ePCI seen on CT within 72 h after surgery. Moreover, we found a significant increase in mortality among ePCIs, as evidenced by subgroup analysis and an E-value of 3.09–6.84, suggesting the robustness of our findings against potential unmeasured confounders.

Some limitations of our study warrant discussion. The use of CT over Magnetic Resonance Imaging (MRI) for ePCI evaluation may underestimate its true incidence by missing small lesions. Early postoperative ICH patients, often in the critical stage, render MRI examinations impractical. CT scanning, with its wide availability, ease of repetition, and short scanning duration, stands out. Hence, CT emerges as the more practical choice for real-world clinical applications in these patients. Our CT scan protocol, involving routine check within 24 h

after surgery and periodic follow-up scans, could introduce detection bias, as critically ill patients receive more frequent scans, increasing the likelihood of identifying cerebral infarctions. At the same time, asymptomatic cerebral infarctions might be missed and underestimated. Additionally, excluding ePCI cases directly caused by surgical manipulation also could underestimate its true occurrence. Surgeon experience and skill significantly influence the occurrence of ePCI directly caused by surgical manipulation. Excluding these cases helps make the remaining ePCI cases more representative and generalizable. Furthermore, the inability to perform vascular status examinations due to poor clinical conditions presents another limitation.

Conclusions

Our results indicate ePCI is a significant complication in patients with supratentorial SICH, and predominantly affects the bleeding side and the MCA territory. It markedly increases postoperative mortality and can be independently predicted by low GCS score, brain herniation, increased intraoperative bleeding, and large preoperative hematoma volume. This discovery enriches our understanding of the impact of ePCI and will help identify high-risk patients in advance. Future studies are needed to establish whether ePCI recognition and prevention after ICH could improve outcomes.

Data availability

The datasets used during the current study are available from the corresponding author upon reasonable request.

Received: 15 April 2024; Accepted: 6 August 2024
Published online: 22 August 2024

References

1. Sacco, S., Marini, C., Toni, D., Olivieri, L. & Carolei,. A. Incidence and 10 year survival of intracerebral hemorrhage in a population-based registry. *Stroke* **40**, 394–399. https://doi.org/10.1161/STROKEAHA.108.523209 (2009).
2. van Asch, C. J. *et al.* Incidence, case fatality, and functional outcome of intracerebral haemorrhage over time, according to age, sex, and ethnic origin: A systematic review and meta-analysis. *Lancet Neurol.* **9**, 167–176. https://doi.org/10.1016/S1474-4422(09)70340-0 (2010).
3. de Oliveira Manoel, A. L. Surgery for spontaneous intracerebral hemorrhage. *Crit. Care* **24**, 45. https://doi.org/10.1186/s13054-020-2749-2 (2020).
4. Mendelow, A. D. *et al.* Early surgery versus initial conservative treatment in patients with spontaneous supratentorial intracerebral haematomas in the International surgical trial in intracerebral haemorrhage (STICH): A randomised trial. *Lancet* **365**, 387–397. https://doi.org/10.1016/S0140-6736(05)17826-X (2005).
5. Mendelow, A. D. *et al.* Early surgery versus initial conservative treatment in patients with spontaneous supratentorial lobar intracerebral haematomas (STICH II): A randomised trial. *The Lancet* **382**, 397–408. https://doi.org/10.1016/s0140-6736(13)60986-1 (2013).
6. Vespa, P. *et al.* ICES (intraoperative stereotactic computed tomography-guided endoscopic surgery) for brain hemorrhage: A multicenter randomized controlled trial. *Stroke* **47**, 2749–2755. https://doi.org/10.1161/STROKEAHA.116.013837 (2016).
7. Hanley, D. F. *et al.* 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. *The Lancet* **393**, 1021–1032. https://doi.org/10.1016/s0140-6736(19)30195-3 (2019).
8. He, J., Fu, F., Zhang, W., Zhan, Z. & Cheng, Z. Prognostic significance of the clinical and radiological haemorrhagic transformation subtypes in acute ischaemic stroke: A systematic review and meta-analysis. *Eur. J. Neurol.* **29**, 3449–3459. https://doi.org/10.1111/ene.15482 (2022).
9. Xu, X. H., Gao, T., Zhang, W. J., Tong, L. S. & Gao, F. Remote diffusion-weighted imaging lesions in intracerebral hemorrhage: Characteristics, mechanisms, outcomes, and therapeutic implications. *Front. Neurol.* **8**, 678. https://doi.org/10.3389/fneur.2017.00678 (2017).
10. Posener, S. *et al.* Remote diffusion-weighted imaging lesions and Intracerebral hemorrhage: A systematic review and meta-analysis. *Stroke* **54**, e133–e137. https://doi.org/10.1161/strokeaha.122.040689 (2023).
11. Lin, K. *et al.* Comparison of endoscopic and open surgery in life-threatening large spontaneous supratentorial intracerebral hemorrhage: A propensity-matched analysis. *Int. J. Stroke* **18**, 569–577. https://doi.org/10.1177/17474930221130892 (2023).
12. Godoy, D. A., Pinero, G. & Di Napoli, M. Predicting mortality in spontaneous intracerebral hemorrhage: Can modification to original score improve the prediction?. *Stroke* **37**, 1038–1044. https://doi.org/10.1161/01.STR.0000206441.79646.49 (2006).
13. Tunkel, A. R. *et al.* 2017 Infectious diseases society of America's clinical practice guidelines for healthcare-associated ventriculitis and meningitis. *Clin. Infect. Dis.* **64**, e34–e65. https://doi.org/10.1093/cid/ciw861 (2017).
14. Fisher, R. S. *et al.* ILAE official report: A practical clinical definition of epilepsy. *Epilepsia* **55**, 475–482. https://doi.org/10.1111/epi.12550 (2014).
15. Yang, J. *et al.* A nomogram to predict the risk of early postoperative ischemic events in patients with spontaneous intracranial hematoma. *Neurosurg. Rev.* **44**, 3557–3566. https://doi.org/10.1007/s10143-021-01533-1 (2021).
16. Jabbarli, R. *et al.* Predictors and impact of early cerebral infarction after aneurysmal subarachnoid hemorrhage. *Eur. J. Neurol.* **22**, 941–947. https://doi.org/10.1111/ene.12686 (2015).
17. Zhi-Ling, C., Qi, L., Jun-Yong, Y. & Bang-Qing, Y. The prevalence and risk factors of posttraumatic cerebral infarction in patients with traumatic brain injury: A systematic review and meta-analysis. *Bioengineered* **13**, 11706–11717. https://doi.org/10.1080/21655979.2022.2070999 (2022).
18. Wu, Y. G. *et al.* Risk factors for cerebral infarction after moderate or severe traumatic brain injury. *Ther. Clin. Risk Manage.* **17**, 433–440. https://doi.org/10.2147/tcrm.s309662 (2021).
19. Zhang, S. *et al.* Clinical evaluation of post-operative cerebral infarction in traumatic epidural haematoma. *Brain Inj.* **31**, 215–220. https://doi.org/10.1080/02699052.2016.1227088 (2017).
20. Zhang, K. *et al.* Risk factors for poor outcomes of spontaneous supratentorial cerebral hemorrhage after surgery. *J. Neurol.* **269**, 3015–3025. https://doi.org/10.1007/s00415-021-10888-w (2022).
21. Leasure, A. C. *et al.* Identification and validation of hematoma volume cutoffs in spontaneous supratentorial Deep intracerebral hemorrhage. *Stroke* **50**, 2044–2049. https://doi.org/10.1161/STROKEAHA.118.023851 (2019).
22. Tjerkstra, M. A. *et al.* A systematic review of viscoelastic testing in patients with subarachnoid hemorrhage. *World Neurosurg.* **175**, 102-112 e105. https://doi.org/10.1016/j.wneu.2023.03.108 (2023).
23. Romoli, M. *et al.* Immunological profile of vasospasm after subarachnoid hemorrhage. *Int. J. Mol. Sci.* https://doi.org/10.3390/ijms24108856 (2023).

24. Regula, J. U., Schill, J., Ringleb, P. A. & Sykora, M. Cerebral vasospasm and delayed cerebral ischemia in intraventricular hemorrhage. *Neurocrit. Care* **20**, 460–465. https://doi.org/10.1007/s12028-013-9897-z (2014).
25. Ikram, A. *et al.* Delayed cerebral ischemia after subarachnoid hemorrhage. *J. Stroke Cerebrovasc. dis. Off. J. Nat. Stroke Assoc.* **30**, 106064. https://doi.org/10.1016/j.jstrokecerebrovasdis.2021.106064 (2021).
26. Goncalves, B. *et al.* Effect of early brain infarction after subarachnoid hemorrhage: A systematic review and meta-analysis. *World Neurosurg.* **115**, e292–e298. https://doi.org/10.1016/j.wneu.2018.04.037 (2018).
27. Phipps, M. S. & Cronin, C. A. Management of acute ischemic stroke. *BMJ* **368**, l6983. https://doi.org/10.1136/bmj.l6983 (2020).
28. Powers, W. J. *et al.* Guidelines for the early management of patients with acute ischemic stroke: 2019 update to the 2018 guidelines for the early management of acute ischemic stroke: A guideline for healthcare professionals from the american heart association/american stroke association. *Stroke* **50**, e344–e418. https://doi.org/10.1161/STR.0000000000000211 (2019).
29. Forlivesi, S., Bovi, P. & Cappellari, M. mechanical thrombectomy for acute ischemic stroke in a patient with concomitant spontaneous intracerebral hemorrhage. *J. Stroke cerebrovasc. Dis. Off. J. Nat. Stroke Assoc.* **26**, e150–e152. https://doi.org/10.1016/j.jstrokecerebrovasdis.2017.04.024 (2017).

Author contributions

KL, YX, RC, contributed to the conception and design of the study. ZC and YH collected the data. KL and CG contributed to statistical analysis. KL and CG wrote the manuscript. YX, RC had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. All authors have read and approved the manuscript.

Funding

This study was supported by the Startup Fund for Scientific Research, Fujian Medical University (2019QH1182) and the Natural Science Foundation of Fujian Province (2021J01387). The funding agency was not involved in the study's design, data collection, analysis, interpretation.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-69571-5.

Correspondence and requests for materials should be addressed to Y.L. or R.J.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.