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Carotid corrected flow time and Doppler shock index for prediction of post-induction hypotension in patients undergoing elective abdominal surgery: a prospective observational study

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Abstract

Background Abdominal surgical patients who have deficient blood volume are at an elevated risk of post-induction hypotension (PIH). New strategies have been adopted, i.e., carotid ultrasound, to evaluate volume status. The study aimed to investigate and compare the predictive value of various carotid ultrasound parameters for PIH.

Methods Adult patients scheduled for abdominal surgery were enrolled. Carotid ultrasound was performed before induction to evaluate the carotid flow time (FT), carotid artery velocity time integral (VTI), and Doppler shock index (the DSI_{FTc} and DSI_{VTI}). Both Wodey's (W) and Bazett's (B) formulae determined the corrected flow time (FTc). The predictive ability of these parameters was analyzed via receiver operating characteristic (ROC) curve analysis.

Results Finally, 94 patients were analyzed, and of those, 40 (42.6%) developed PIH. The areas under the curve for FT, FTc(W), $1/DSI_{FTc}$, and FTc(B) were 0.790 (95% CI 0.697–0.883) ($P<0.05$), 0.788 (95% CI 0.695–0.881) ($P<0.001$), 0.729 (95% CI 0.626–0.832) ($P<0.001$), and 0.689 (95% CI 0.582–0.796) ($P<0.05$), respectively. The optimal cut-off for FTc(W) was 334.15 ms (sensitivity 82.5%, specificity 70.4%), while for FT, it was 313.33 ms (sensitivity 72.5%, specificity 79.6%), indicating FTc(W) as the best predictor among these various parameters. The $1/DSI_{FTc}$ was an inferior predictor of PIH, with an optimal cutoff value of 4.58. The sensitivity (80.0%) and specificity (61.1%) values were obtained.

Conclusion Carotid flow time corrected by Wodey's formula was a reliable indicator of PIH in patients undergoing elective abdominal surgery, superior to FT, DSI_{FTc}, and FTc(B).

Keywords Carotid ultrasound, Post-induction hypotension, Carotid corrected flow time, Doppler shock index, Elective abdominal surgery

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Introduction

Previous studies have indicated that 51% of patients who undergo elective abdominal surgery experience post-induction hypotension (PIH), which is primarily caused by inadequate blood volume resulting from prolonged fasting and gastrointestinal preparation before surgery, as well as the cardiovascular suppressive effects of specific induction agents (Aissaoui et al. 2022). It is related to higher demand for healthcare resources (Stapelfeldt et al. 2021) and more severe complications after surgery, such as kidney problems (Shaw et al. 2022; Salmasi et al. 2017), myocardial injury (Salmasi et al. 2017), and increased death rates (Monk et al. 2015). Therefore, to diagnose and prevent the onset of PIH, the initial crucial measure is to precisely and rapidly evaluate the volume level and fluid responsiveness of these patients before surgery.

Recently, ultrasound technology has been extensively used to evaluate volume during the perioperative phase. To address challenges in assessing patients with high abdominal fat accumulation and excessive intestinal gas (Barbier et al. 2004), studies have explored alternative methods for predicting PIH. Some methods involve a substitute for the collapsibility index and diameter of the inferior vena cava (Peachey et al. 2016) are the collapsibility index of the axillary vein (Chen et al. 2023) and subclavian vein diameter (Wang et al. 2024). However, venous ultrasonography indices do have some drawbacks, including their vulnerability to the patient's respiratory effort and patterns (Airapetian et al. 2015).

Currently, the best correlation between PIH and some arterial system parameters, such as dynamic arterial elastance (Oh et al. 2023) and velocity time integral (VTI) of the left ventricular outflow tract (Aissaoui et al. 2022), has gradually attracted the attention of clinicians. Meanwhile, carotid ultrasound measurement, which is non-invasive, superficial, and unaffected by respiration (van Houte et al. 2023; Mackenzie et al. 2015), can be used as a new method for predicting fluid responsiveness. This approach has shown promising results due to the similarity of carotid blood flow characteristics to the outflow tract of the aorta.

Research has indicated that the corrected flow time (FTc) recorded in the carotid artery relates inversely to the afterload and is influenced by the preload (Mackenzie et al. 2015; Kim et al. 2021). It was determined via both Bazett's (B) and Wodey's (W) formulae (van Houte et al. 2023; Kim et al. 2021). Several studies (Huang et al. 2024; Wang et al. 2022; Maitra et al. 2020) have explored the efficacy of different formulas of FTc in predicting PIH in patients with various clinical scenarios, but few have compared these two formulas simultaneously.

Moreover, research has demonstrated that the FTc(W) and carotid artery maximum VTI can precisely identify the high stroke volume from simulated hemorrhage to transfusion in healthy participants (Kenny et al. 2022). Further, two variants of a new metric, the Doppler shock index (the DSI_{VTI} and DSI_{FTc}), can properly recognize mild-to-severe central hypovolemia in lower body negative pressure (Kenny et al. 2021). Only a few studies have reported whether the new DSI can accurately predict or provide improved prediction of PIH. Therefore, this study was planned to examine and compare the predictive value of carotid ultrasound parameters for PIH in abdominal surgical patients and identify the most effective predictors.

Materials and methods

Study population

The Ethics Committee of Jinling Hospital approved this prospective observational study on December 28, 2023 (2023DZKY-104–02), registered in the Chinese Clinical Trial Registry (ChiCTR2400081370). Written informed consent was collected from all enrolled patients before their participation. Patients (18 to 65 years, ASA physical status II or III) who had planned for abdominal surgery under general anesthesia were the participants of this study. The study did not include those patients who reported any of the following: mean arterial pressure (MAP) > 120 mmHg before anesthesia; any previous record of neck surgery or trauma; chronic liver deficiency; acute renal injury; chronic cardiovascular disease; pregnant or lactating women; oral angiotensin receptor blockers or angiotensin-converting enzyme inhibitors (ACEI); lateral, prone, and lithotomy operations; and body mass index (BMI) > 30 kg/m^2 or < 15 kg/m^2. Further, patients who lacked distinct, reliable measurement data, and ultrasound images were not included in the study.

Methods for ultrasound measurement

The ultrasound examination was carried out in line with the established protocols, employing an ultrasound machine (Wisonic, China). The patient was positioned in a supine position, with the right side of the neck completely exposed. The transverse part of the main carotid artery beneath the thyroid cartilage was precisely identified via a linear array probe (4–15 MHz), with the marker directed toward the patient's head. Thus, the sampling line was positioned at the center of the carotid lumen, around 2 cm from the carotid bifurcation, and the electronic angle correction cursor pointed in the direction of blood flow. Insonation angles between the ultrasound beam and blood flow were maintained at or < 60°. Next, the carotid blood flow waveform was acquired, and the consecutive stable carotid pulse Doppler flow spectrum was determined with an optimal level of image quality.

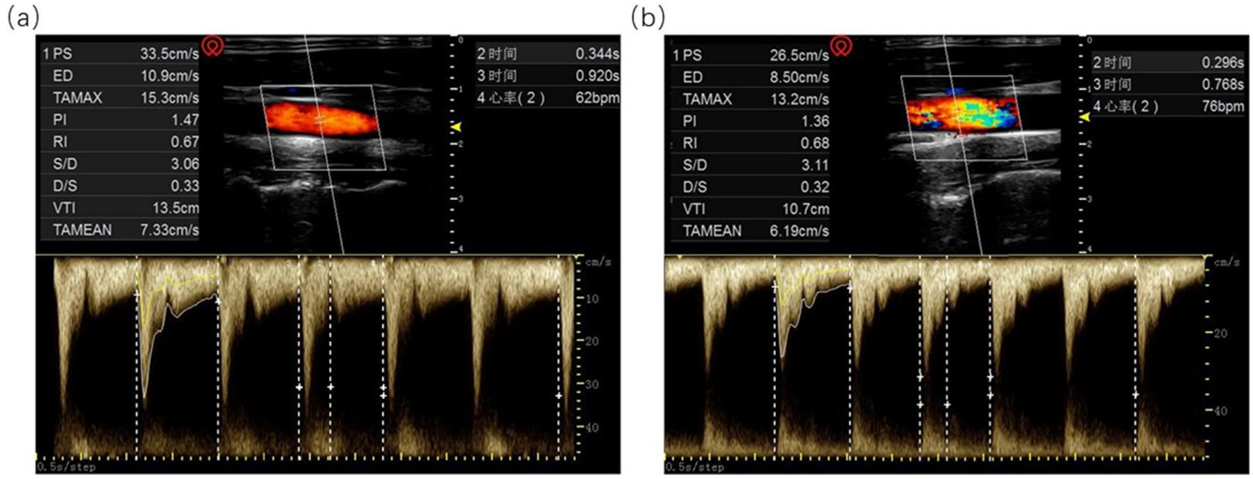

Fig. 1 Typical carotid artery flow Doppler spectrograms in the normal conditions and hypovolemic conditions. **a** In the normal conditions, VTI was obtained; time 2 was the FT and time 3 was the CT. HR from ultrasound was also obtained. **b** In the hypovolemic conditions, VTI was obtained; time 2 was the FT, and time 3 was the CT. HR from ultrasound was also obtained. FT, flow time; CT, cycle time; HR, heart rate; VTI, velocity time integral

Finally, carotid ultrasound parameters were manually extracted offline and measured three times to calculate the average value by a trained independent physician (Fig. 1). Flow time (FT), which is known as the time period between the systolic increase phase and dicrotic notch, was calculated and then adjusted for heart rate (HR) via two distinct equations outlined below (van Houte et al. 2023; Kim et al. 2021):

$$\text{Wodey's (W) equation: FTc(W)} = \text{FT} + 1.29 * (\text{HR} - 60)$$

$$\text{Bazett's (B) equation: FTc(B)} = \text{FT}/\sqrt{\text{cycle time}}$$

The area under the maximal velocity trace in a single cardiac cycle, which represents the distance covered by the fastest-moving red blood cells per cardiac cycle in cm, was defined as the VTI (Kenny et al. 2021).

The DSI_{FTc} and DSI_{VTI} were defined as heart rate (HR) from ultrasound divided by FTc(W) and VTI, respectively (Kenny et al. 2021).

Anesthesia management

The anesthesiologist responsible for the patient was intentionally blinded to the results of the carotid Doppler measurement. No premedication was administered, and it is necessary to adhere to standard fasting procedures. Vital signs, including pulse oxygen level, HR, electrocardiogram, and electroencephalographic bispectral index (BIS), were recorded during the operative period. Ringer's acetate solution was intravenously injected at 10 mL/kg/h. The radial artery level was the site of continuous arterial pressure monitoring with an arterial catheter.

The standard routine sequence induction was followed by the anesthesia induction regimen: 0.04 mg/kg midazolam, 2 mg/kg propofol, 0.3 μg/kg sufentanil, and 0.15 mg/kg cisatracurium (Wang et al. 2024). After 3 min of mask ventilation, video laryngoscopy was employed for tracheal intubation. Then, to maintain a BIS score between 40 and 60, propofol was adjusted to 4–10 $mg{\cdot}kg^{-1}{\cdot}h^{-1}$ and remifentanil to 8–15 $\mu g{\cdot}kg^{-1}{\cdot}h^{-1}$. The respiratory rate was adjusted to maintain the end-tidal CO_2 between 35 and 40 mmHg, while the basal ventilation tidal volume remained at 6–8 mL/kg with a 12 frequency.

Study design

In the course of the operation, the monitor (Mindray, China) recorded MAP and HR every 1 min. The baseline MAP (T0 MAP) was determined as the blood pressure value 1 min before induction. In the induction period, the lowest MAP and associated HR were documented. Considering the different definitions of the post-induction period (Aissaoui et al. 2022), minimum MAP at two time points were also separately recorded: between induction of anesthesia and intubation (T1 MAP), and within 10 min after intubation (T2 MAP). Strict protocols were followed up to 10 min after intubation to reduce irritation and keep the patient's position unchanged.

Moreover, PIH episodes were identified as a MAP decrease of over 30% from the baseline level or any observed period of MAP $<$ 65 mmHg for $\geq$ 1 min between induction and 10 min post-intubation (Wang et al. 2024). Phenylephrine boluses (20 μg) were administered to patients with PIH. In cases of bradycardia ($<$ 40 beats/min), atropine (0.5 mg) was administered. Patients were categorized into two groups, PIH and Non-PIH, dependent upon the presence of hypotension during the study.

Sample size and statistical analysis

The sampling size was determined via the PASS 15.0 software. Maitra et al. observed an area under the receiver operating characteristic (AUC) curve of 0.91 for FTc(W) to predict hypotension in adult patients after general anesthesia induction (Maitra et al. 2020). This study established an AUC of 0.70 by assuming a conservative predictive value for FTc(W). Considering these assumptions, a sample size of 92 patients was determined with $\alpha = 0.05$ and $1\text{-}\beta = 0.80$ and a dropout rate of 10%. Thus, approximately 102 patients were selected for the analysis.

Data was statistically computed via SPSS v25.0 (IBM, USA) and MedCalc v22.0 (MedCalc Software, Belgium). Inter-group differences were compared using an independent sample *t*-test, and continuous data with a normal distribution were expressed as mean ± SD ($\bar{x} \pm s$). Mann–Whitney *U* test was employed to compare medians [interquartile ranges] of non-normally distributed continuous data. Results were illustrated in numerical values and percentages for categorical variables, and the χ^2 test was undertaken for analysis. This study used the generalized estimating equation (GEE) to compare continuous, non-normally distributed factors at various time points. Moreover, $p < 0.05$ was regarded as statistically significant.

The association between the formation of PIH and carotid artery-related parameters was examined using a binary logistic regression analysis. The study has established two multivariate logistic regression models. Due to the substantial correlation between age and carotid artery-related factors (Sun et al. 2022), individual age was added as a variable in model 1. Confounding variables were selected based on clinical practice and previous findings. These variables consisted of ASA physical status, age, sex, BMI, albumin levels, baseline MAP, and baseline HR. The receiver operating characteristic (ROC) was used to evaluate the potential of carotid artery-related parameters to predict PIH in line with the trial findings. Optimal threshold values, the AUC, and a 95% confidence interval (CI) were also computed.

Multivariate linear regression was also conducted to evaluate the correlation between carotid ultrasound-related indicators and the reduced MAP. After adjusting for the abovementioned confounding variables, the models with the largest adjusted R^2 were selected.

Results

PIH incidence and characterization

This trial recruited approximately 102 patients. Among them, 9 were excluded from the study, 2 had insufficient ultrasound images, and 1 had taken ACEI drugs before the surgery. Moreover, 5 patients dropped out of the trial, 3 of them experienced unsuccessful arterial cannulation, 1 had missing MAP data, and 1 had a baseline MAP > 120 mmHg. Last, data from all 94 patients were examined. Out of these, 40 patients (42.6%) developed PIH (Fig. 2). A MAP of < 65 mmHg and a > 30% reduced MAP was observed in 17 patients with PIH, while 11 patients only experienced a > 30% reduction in MAP.

Patient baseline characteristics

Clinical baseline values and patient demographics, such as age, sex, BMI, ASA physical status, hypertension, drinking and smoking history, history of surgical abdominal procedures, surgical procedures, hemoglobin, and prognostic nutritional index (PNI) (Ding et al. 2022), failed to show substantial variations. Patients with PIH, inversely, demonstrated lower albumin levels ($p = 0.046$) than those without PIH (Table 1).

Hemodynamics and ultrasound measurements

In comparison, patients with PIH showed smaller FT ($p = 0.002$), CT ($p = 0.002$), FTc(W) ($p < 0.001$), FTc(B) ($p = 0.002$), and VTI ($p = 0.037$), as well as higher DSI_{FTc} ($p < 0.001$) and DSI_{VTI} values ($p = 0.014$). Meanwhile, patients with PIH demonstrated higher baseline HR ($p = 0.031$), HR from ultrasound ($p = 0.006$), and HR at the lowest MAP ($p = 0.020$) (Table 2). Decreases in MAP were negatively correlated with the FT ($r = -0.34$, $p < 0.01$) and FTc(W) ($r = -0.28$, $p < 0.01$), while they were positively correlated with DSI_{FTc} ($r = 0.30$, $p < 0.01$) (Fig. 3).

The MAP results for the groups between pre-induction and 10 min post-intubation are presented in Table 3. The GEE results showed that there were no substantial variations in baseline MAP between the groups ($p = 0.677$). However, the PIH group revealed higher T1 MAP and T2 MAP than the non-PIH group ($\chi^2 = 23.485$, $p < 0.001$). Furthermore, there was an interaction effect between group and time ($\chi^2 = 31.721$, $p < 0.001$), and the trajectory of MAP change over time was substantially different between both groups.

Univariate and multivariate analyses

Univariate analysis depicted that PIH was correlated to FT, FTc(W), FTc(B), DSI_{FTc}, VTI, and DSI_{VTI}. The original OR value of DSI_{FTc} was too large, and then, DSI_{FTc} was converted to its reciprocal ($1/DSI_{FTc}$) for analysis. After adjustment for age (model 1), these variables were separately associated with PIH. After further adjusting for confounding variables (model 2), FT ($p < 0.01$), FTc(W) ($p < 0.01$), FTc(B) ($p < 0.01$), and $1/DSI_{FTc}$ ($p < 0.01$) were still separately found to be independent PIH predictors (Table 4).

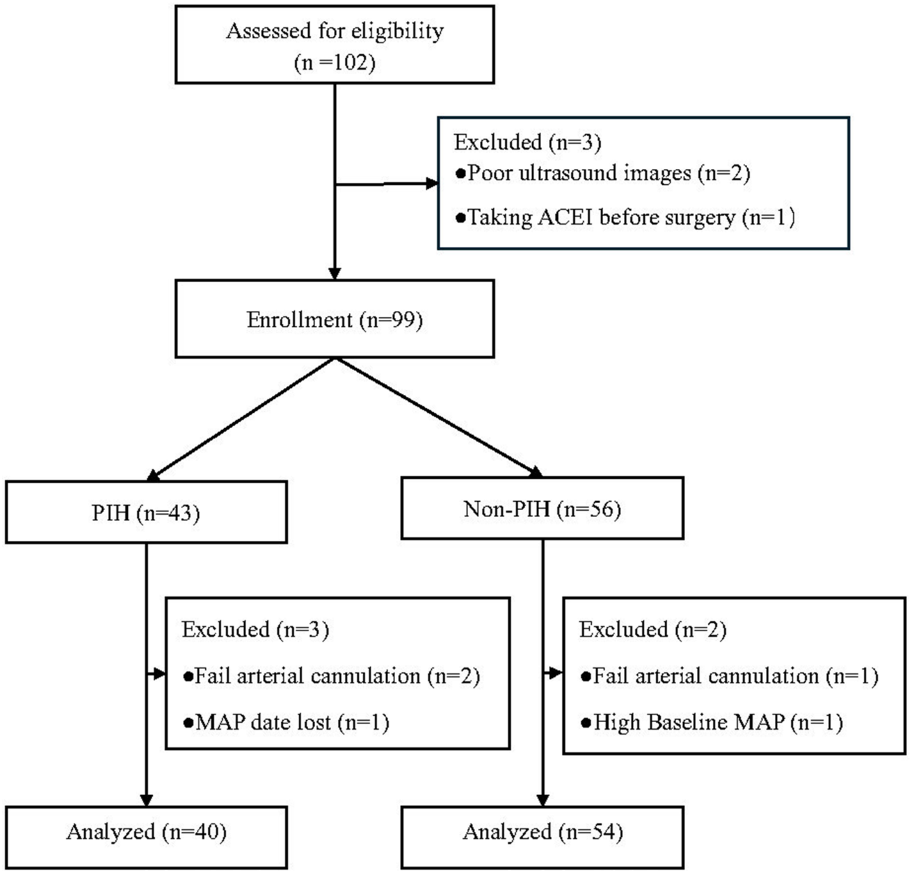

Fig. 2 Study flow chart

Predictive value of various carotid ultrasound parameters

The predictive value of the FT, FTc(W), FTc(B), and DSI_{FTc} for PIH was analyzed via logistic regression. The best possible cutoff value (313.33 ms) resulted in sensitivity (72.5%) and specificity (79.6%) values when FT was used as a predictor (AUC 0.79; 95% CI 0.697–0.883; $p<0.001$). It also demonstrated acceptable diagnostic value. Meanwhile, FTc(W) demonstrated comparable diagnostic precision (AUC 0.788; 95% CI 0.695–0.881; $p<0.001$), with a practical cutoff value of 334.15 ms, resulting in sensitivity (82.5%) and specificity (70.4%) values. The AUC for $1/DSI_{FTc}$ was 0.729 ($p<0.001$; 95% CI 0.626–0.832), with an acceptable cutoff value of 4.58. Thus, the specificity (61.1%) and sensitivity (80.0%) values were obtained. FTc(B) was correlated to a ROC of 0.689 ($p=0.002$; 95% CI 0.582–0.796), which was less than that of $1/DSI_{FTc}$ (0.729). The sensitivity (77.5%) and specificity (66.1%) values were obtained with the ideal cutoff value of 352.16 ms for FTc(B) (Fig. 4).

Multiple linear regression

After collinearity diagnosis and linear regression analysis, the regression models separately, including FTc(W) and FT, show the same largest adjusted $R^2=0.375$ ($p<0.01$). It was also found that age ($p<0.01$) and baseline MAP ($p<0.01$) showed a considerable positive relationship with the decline of MAP after induction, while FTc(W) ($p<0.01$) and FT ($p<0.01$) demonstrated a remarkable negative correlation (Table 5).

Based on the intraclass correlation coefficient (good if it exceeds 0.80), we assessed the intra-observer variability of FT and CT for a single observer, which were 0.94 and 0.96, respectively.

Discussion

This study found that pre-induction carotid ultrasonography measurements were predictive of PIH during elective abdominal surgery. The analysis showed that FTc(W) could offer great predictive value (AUC 0.788; 95% CI 0.695–0.881), with an optimal cutoff value of 334.15 ms, resulting in sensitivity (82.5%), and specificity (70.4%) values. Considering the results of the ROC and sensitivity value, FTc(W) was a better predictor compared to FT, DSI_{FTc}, and FTc(B).

The current GEE results demonstrated that as baseline MAP remained similar in both groups, there was a

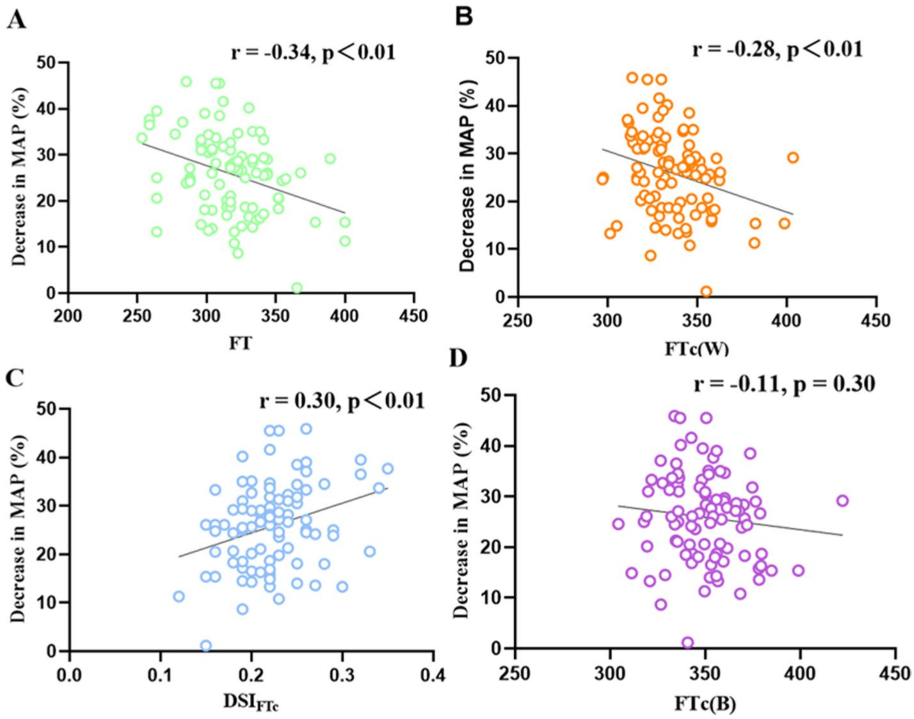

Fig. 3 The scatter and correlation diagrams of the decrease in MAP for FT, FTc(W), DSI_{FTc}, and FTc(B). FT, carotid flow time; FTc(W), carotid flow time corrected by Wodey's equation; DSI_{FTc}, Doppler shock index with FTc in the denominator; FTc(B), carotid flow time corrected by Bazett's equation; MAP, mean arterial blood pressure. The dashed line is the trend line

Table 1 Patient baseline characteristics

	PIH (*n* = 40)	Non-PIH (*n* = 54)	*P*
Age (years)	50.5 [36.3–58.0]	46.0 [34.8–55.0]	0.215
Sex (male/female)	22/18	27/27	0.631
BMI, kg/m^2	20.8 ± 3.3	22.0 ± 3.0	0.058
ASA (II/III)	53/1	37/3	0.180
Hypertension, *n* (%)	1 (3)	6 (11)	0.116
Smoker (yes/no)	10/30	12/42	0.753
Drinker (yes/no)	7/33	10/44	0.899
History of surgical abdominal procedures, *n* (%)	13 (33)	20 (37)	0.669
Surgical procedures			0.536
Laparoscopic cholecystectomy, *n* (%)	5 (12.5)	12 (22)	
Colorectal surgery, *n* (%)	32 (80)	39 (72)	
Gastrectomy, *n* (%)	2 (5)	1 (1.8)	
Pancreatic surgery, *n* (%)	1 (2.5)	2 (3.7)	
Hemoglobin, g/L	126.0 ± 20.4	130.5 ± 19.9	0.285
Albumin, g/L	41.1 [36.0–44.8]	43.2 [38.6–45.9]	0.046
Prognostic nutritional index	49.4 [45.0–53.4]	51.2 [47.0–55.0]	0.097

Nutritional status was assessed via prognostic nutritional index (PNI), which was calculated as albumin (g/L) + 5 × total lymphocyte count (10^9/L). Normally distributed results were reported as mean ± standard deviation ($\overline{x} \pm s$), while non-normally distributed data were expressed as medians [interquartile ranges]

BMI body mass index, *ASA* American Society of Anesthesiologists

Table 2 Comparison of hemodynamics and ultrasound measurements between patients with or without PIH

	PIH ($n=40$)	Non-PIH ($n=54$)	*P*
Baseline MAP, mmHg	92.5 ± 13.3	93.7 ± 10.0	0.627
Baseline HR, beats/min	79.4 ± 12.4	73.8 ± 12.2	0.031
lowest MAP, mmHg	61.8 ± 6.0	73.6 ± 6.3	< 0.001
Decrease in MAP (%)	32.5 ± 7.0	21.0 ± 6.5	< 0.001
HR at the lowest MAP, beats/min	74.5 ± 15.6	67.4 ± 13.5	0.020
HR from ultrasound, beats/min	78.9 [71.0–84.8]	71.5 [63.0–78.3]	0.006
FT, ms	301.67 ± 23.65	329.14 ± 27.43	< 0.001
CT, ms	779.80 ± 121.80	864.54 ± 134.71	0.002
FTc(W), ms	326.08 ± 13.33	343.99 ± 19.70	< 0.001
FTc(B), ms	342.97 ± 15.32	355.40 ± 20.62	0.002
DSI_{FTc}	0.24 ± 0.04	0.21 ± 0.04	< 0.001
VTI, cm	13.0 ± 2.7	14.4 ± 3.3	0.037
DSI_{VTI}	6.5 ± 2.3	5.4 ± 2.0	0.014

MAP Mean arterial pressure, *HR* Heart rate, decrease in MAP = (baseline MAP − lowest MAP)/baseline MAP × 100%; *FT* Flow time, *CT* Cycle time, *FTc(W)* Carotid flow time corrected by Wodey's equation, *FTc(B)* Carotid flow time corrected by Bazett's equation, DSI_{FTc} and DSI_{VTI} Doppler shock index with FTc and VTI in the denominator; *VTI* Velocity time integral

Table 3 MAP at different time points in the two groups

Group	Time			χ^2	*P*
	T0	T1	T2		
Non-PIH ($N=54$)	92.0 [86.8–101.0]	76.0 [72.8–81.0] [a]	73.5 [68.8–78.5] [a,b]	85.531	< 0.001
PIH ($N=44$)	94.0 [81.3–102.2]	66.0 [60.3–73.8] [a]	61.5 [58.3–67.0] [a,b]	66.594	< 0.001
Z	−0.417	−4.946	−6.611		
P	0.677	< 0.001	< 0.001		

Wald χ^2 group = 23.485; Wald χ^2 time = 664.083; Wald χ^2 interaction effect = 31.721

MAP Mean arterial pressure, *T0 MAP* Baseline MAP, *T1 MAP* Minimum MAP between induction of anesthesia and intubation, *T2 MAP* Minimum MAP within 10 min after intubation

P group = 0.01

P time = 0.01

P interaction effect = 0.01

Compared to T0 MAP, [a]$P < 0.05$; compared to T1 MAP, [b]$P < 0.05$.

Table 4 Predictive factors for PIH

Predictors	Unadjusted analysis OR [95% CI]	Adjusted analysis OR [95% CI]	
		Model 1	Model 2
FT, ms	0.955 [0.933–0.977] **	0.947 [0.924–0.971] **	0.921 [0.883–0.960]**
FTc(W), ms	0.931 [0.900–0.964] **	0.915 [0.878–0.953] **	0.904 [0.859–0.951] **
FTc(B), ms	0.962 [0.937–0.987] **	0.954 [0.927–0.982] **	0.933 [0.898–0.969] **
$1/DSI_{FTc}$	0.328 [0.173–0.624] **	0.294 [0.150–0.577] **	0.124 [0.037–0.417] **
VTI, cm	0.864 [0.751–0.994] *	0.854 [0.740–0.985] *	0.860 [0.725–0.1.021]
DSI_{VTI}	1.278 [1.041–1.569] *	1.307 [1.060–1.611] *	1.310 [0.966–1.776]

FT Flow time, *FTc(W)* Carotid flow time corrected by Wodey's (W) equation, *FTc(B)* Carotid flow time corrected by Bazett's (B) equation, DSI_{FTc} Doppler shock index with FTc in the denominator, *VTI* Velocity time integral, DSI_{VTI} Doppler shock index with VTI in the denominator

Model 1: Adjusted for age Model 2: Adjusted for age, sex, ASA physical status, albumin levels, BMI, baseline MAP, and baseline HR

* $P < 0.05$

***P* < 0.01

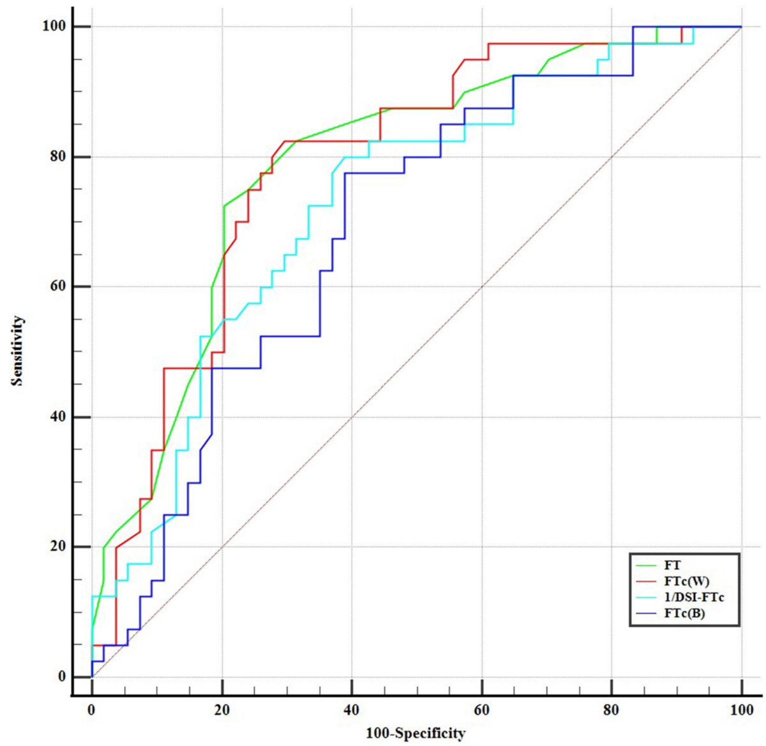

Fig. 4 Comparison of receiver operating characteristic (ROC) curves of FTc(W), FT, 1/DSI_{FTc}, and FTc(B) to predict PIH. FT, carotid flow time; FTc(W), carotid flow time corrected by Wodey's equation; FTc(B), carotid flow time corrected by Bazett's equation; and DSI_{FTc}, Doppler shock index with FTc in the denominator

Table 5 Multivariate linear regression models for prediction of a decrease in mean arterial blood pressure after induction of anesthesia

	***β* OR (95% confidence interval)**	
	Model 3	**Model 4**
Age (years)	0.342 (0.109 ~ 0.378)**	0.355 (0.117 ~ 0.389)**
Sex	− 0.007 (− 3.347 ~ 3.086)	− 0.001 (− 3.175 ~ 3.211)
BMI, kg/m^2	− 0.157 (− 0.980 ~ 0.111)	− 0.183 (− 1.057 ~ 0.044)
ASA physical status[a]	− 0.049 (− 9.786 ~ 5.514)	− 0.047 (− 9.688 ~ 5.608)
Albumin levels, g/L	− 0.068 (− 0.404 ~ 0.186)	− 0.038 (− 0.359 ~ 0.238)
Baseline MAP, mmHg	0.454 (0.199 ~ 0.496)**	0.442 (0.191 ~ 0.487)**
Baseline HR, beats/min	0.105 (− 0.049 ~ 0.196)	− 0.064 (− 0.201 ~ 0.111)
FT, ms	—	− 0.407 (− 0.192 ~ − 0.053)**
FTc(W), ms	− 0.329 (− 0.233 ~ − 0.065)**	—

BMI Body mass index, *ASA* American Society of Anesthesiologists, *MAP* Mean arterial blood pressure, *HR* Heart rate, *FTc(W)* carotid flow time corrected by Wodey's (W) equation.

[a] reference group is ASA physical status II

***P* < 0.01

substantial decrease in MAP after induction. Mainly, this reduction was more significant in the PIH group, which continued to decline even with the stimulation resulting from intubation. This phenomenon could be associated with the presence of an occult hypovolemic state in patients before abdominal surgery (Myles et al. 2018). However, factors such as tension and anxiety may trigger a stress response, resulting in the maintenance of blood pressure within the normal range in some patients with hypertension (Chiu et al. 2023). In exploring the various mechanisms underlying PIH, including weakened myocardial contractility and venous and arterial dilation, this study focused on the arterial system, which was driven by findings from previous research conducted under a comparable induction protocol. It indicated that PIH may stem from decreased systemic vascular resistance attributed to arterial dilation (Saugel et al. 2022). For instance, FTc could demonstrate improved predictive capability by primarily indicating pre-anesthetic preload while not disregarding its association with afterload (Kim et al. 2021).

The incidence of PIH in surgical patients differs due to various considerations. First, some studies (Huang et al. 2024; Maitra et al. 2020) focused only on 3 min after induction because direct laryngoscopy and tracheal intubation can cause sympathetic nerve stimulation and lead to an alteration in blood pressure. However, the jaw thrust, stretching pharyngeal and laryngeal mucosa, and activating rapid adaptation receptors can also cause sympathetic responses (Park et al. 2013). The current GEE results also indicate the importance of monitoring the initial 10 min post-intubation. Moreover, in addition to the absolute threshold of 65 mmHg, we also included the criterion of a 30% reduction from baseline MAP as a composite outcome, which is also accepted in some studies (Wang et al. 2024; Huang et al. 2024; Fechner et al. 2024). This reduction is strongly associated with myocardial and kidney injury (Salmasi et al. 2017) and postoperative ischemic stroke (Bijker et al. 2012) and is a commonly used treatment threshold (Futier et al. 2017). Moreover, our study actually included some patients with well-controlled hypertension who may need MAP within a certain baseline range for adequate organ perfusion (Salmasi et al. 2017). Furthermore, the selected induction regimens varied, with factors including anesthetic agents, dose selection, and mode of administration. In this study, pharmacological agents were administered according to the patient's actual weight to reduce the influence of anesthetics on PIH.

In this study, the univariate analysis of age was not significant; however, upon examining the substantial correlation between age and the carotid artery (Sun et al. 2022), the analysis revealed that age emerged as an independent predictor after the adjustment for confounding variables via multi-factor analysis. Meanwhile, in the selected regression model, age and baseline MAP were substantially and positively associated with MAP reduction after induction. Carotid vascular elasticity probably controls vascular resistance resulting from blood vessel bending for appropriate blood flow. However, this regulating capacity diminishes with aging (Sun et al. 2022). Dolichocarotids may be aggravated with aging, which is potentially related to the occurrence of cardiovascular and cerebrovascular events (Ciccone et al. 2014). Further, it was found that patients with PIH had lower levels of albumin relative to patients without PIH, which was consistent with findings from previous studies (Wang et al. 2024; Shao et al. 2022). The observed similarities can be related to the decrease in plasma colloid osmotic pressure and plasma water content in patients with low levels of albumin (Margarson and Soni 1998). Thus, based on Wang et al. (2024), it is suggested that administering a small dose of colloids before anesthesia might lower the chances of PIH in patients. However, more research is needed to explore this finding.

The optimal cutoff value of FTc(W) in this study was near the previously reported 334.95 ms in elderly individuals (Huang et al. 2024). Multiple factors, including inflammatory factor release, insufficient volume, and weakness, may contribute to this occurrence in both special populations. The AUROC of FTc(W) was marginally lower than in other studies (Wang et al. 2022; Chowdhury et al. 2023), but it was still clinically significant and superior to other parameters. Presumably, this result is due to the fact that Wodey's formulae are adequately correct for HR and are not influenced by it (Mohammadinejad and Hossein-Nejad 2018). Kim et al. demonstrated that FTc(W) was a better predictor than FTc(B) for hypotension after spinal anesthesia, which is in line with the current findings (Kim et al. 2021). A previous study (Chowdhury et al. 2023) also found that FTc(B) did not significantly predict PIH in patients undergoing emergency laparotomy for perforation peritonitis. In these patients, systemic inflammation probably occurs, which leads to modifications in vascular physiology, including a weakened systemic vascular response. Specific functional hemodynamic tests have been adopted to evaluate fluid responsiveness by changing cardiac preload, such as the passive limb raising test (Aissaoui et al. 2022; Mackenzie et al. 2015) and the simulated end-inspiratory occlusion maneuver (sEIOT). FTc changes obtained from these cumbersome relative tests may be more predictive than absolute values. Jin et al. demonstrated that PIH can be accurately predicted by differences in FTc(W) caused by sEIOT, with a threshold of < 16.57% (Jin et al. 2024).

Limitations

First, the limitations associated with carotid ultrasound for volume measurement include surgical interventions in the region and the underlying pathology of carotid vessels, including crucial stenosis, arrhythmia, and compromised brain autoregulation. Second, echocardiography or cardiac output monitoring was not used to evaluate cardiac contractility and total body volume. Further studies are needed to validate fluid responsiveness using the above monitoring devices. Third, the study was conducted at a single center in China with a limited sample size, which may introduce biases and limit the generalizability of the findings. However, we have also conducted a post hoc sample size calculation and found that the current sample size can meet our requirements. Moreover, manual induction was used in this study, whereas target-controlled infusion may more reliably reflect the hemodynamic profile. Last, offline measurements were performed manually.

Conclusions

Among dependable indicators for PIH in abdominal surgical patients, FTc(W) performs better than FT, DSI_{FTc}, and FTc(B), whereas VTI and DSI_{VTI} were ineffective in predicting PIH. Further studies may examine the relevance of this approach in patients with planned abdominal surgical procedures via integrated fluid management methods and automatic carotid flow measurement algorithms.

WHAT IS KNOW

- Post-induction hypotension is common in patients planned for elective abdominal surgery.
- Carotid ultrasound, as a new strategy, has been used to assess volume status.

WHAT IS NEW

- Patients, especially those experiencing PIH, frequently exhibit a temporary increase in MAP after intubation stimulation while still facing the potential for continuing decline.
- DSI_{FTc} can also predict PIH in abdominal surgical patients.
- Among dependable indicators for PIH, FTc(W) performs best compared to FT, DSI_{FTc}, and FTc(B).

Authors' contributions

TS, K-LH , L-WR and M-LD contributed to the study's conception and design. M-LD supervised this study. TS and K-LH performed material preparation and data collection. TS and L-WR performed data analysis. The first draft of the manuscript was written by TS and H-WQ. L-WR, M-TH, X-YS, J-WX, H-WQ and Manlin Duan commented on previous versions of the manuscript. All authors read and approved the final of the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was performed in line with the principles of the Declaration of Helsinki. Ethical approval for this study (2023DZKY-104–02) was provided by the ethics committee of the Jinling Hospital on December 28, 2023. Written informed consent was obtained from all eligible patients.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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