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Original Article

Prediction of mechanical ventilation outcome by early abdominal-visceral-blood-flow-and-function score in critically ill patients after cardiopulmonary bypass in the ICU: A prospective observational study

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ABSTRACT

Background: Abdominal organs are important organs that sense and respond to ischemia and hypoxia, but there are few evaluation methods. We use ultrasonography to evaluate abdominal organ function and blood flow in patients with mechanical ventilation (MV) after cardiopulmonary bypass and to obtain a semiquantitative score for abdominal organ function and blood flow.

Methods: Patients with cardiopulmonary bypass in the Critical Care Department of Peking Union Medical College Hospital in China from March to July 2021 were enrolled in this prospective observational study. The correlation of the abdominal-visceral-blood-flow-and-function score (AVBFS) with the duration of MV, number of days spent in the intensive care unit (ICU), acute physiology and chronic health evaluation II (APACHE-II), sequential organ failure assessment (SOFA), lactate, epinephrine, and norepinephrine use was analyzed, and the results were used to assess the predictive value of the receiver operating characteristic curve (ROC) regression analysis score for the duration of MV.

Results: Of the 92 patients who underwent cardiopulmonary bypass, 41 were finally included. The AVBFS were significantly correlated with the duration of MV, number of days spent in the ICU, APACHE-II score, SOFA score, and norepinephrine use time. The AVBFS in a group of patients using ventilators ≥36 h were significantly higher than those obtained for a group of patients using ventilators <36 h (P <0.05). The evaluation results for the AVBFS at 0-12 h after ICU admission were as follows: area under the ROC curve (AUC)=0.876 (95% confidence interval [CI]: 0.767 to 0.984), cut-off value=2.5, specificity=0.842, and sensitivity=0.773.

Conclusions: Abdominal visceral organ function and blood perfusion can be used to evaluate gastrointestinal function. It is related to early and late extubation after cardiac surgery.

Introduction

Gastrointestinal dysfunction caused by cardiopulmonary bypass in heart surgery and acute renal injury are risk factors affecting the clinical prognosis of patients. The reported mortality rate of multiple organ failure caused by gastrointestinal (GI) complications is 15%–63%.[1] Cardiopulmonary bypass can affect renal function in up to 30% of patients and may lead to the development of renal failure.[2] Damage to visceral blood perfusion or uneven blood flow distribution resulting from cardiopulmonary bypass is the main cause of postoperative complications.[3] At present, the organ dysfunction scores

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in wide use do not include an assessment of the GI system and organ blood flow problems.[4–6] A test of acute gastrointestinal injury (AGI) relying on symptoms alone increases the likelihood of confounding factors. Furthermore, it does not provide a means of serially assessing changes in the severity of GI tract function, GI blood flow, or the influence of other organs. Thus, it is not possible to respond to abdominal organ dysfunction early and continuously.[7]

Ultrasonic examination is a nonradiative, safe, inexpensive, and noninvasive imaging technique that is easy to use and has good repeatability.[8–10] The European Federation of Societies for Ultrasound in Medicine and Biology (EFSUMB) developed recommendations and guidelines for GI ultrasonography in 2014 that provide criteria and diagnostic strategies for GI ultrasonography.[11] In some studies, the sensitivity and specificity of gastrointestinal ultrasound (GIUS) have been reported to be similar to those of computed tomography (CT) and superior to those of X-ray plain film.[12] Some scholars have also proposed a semiquantitative evaluation of renal blood flow by color Doppler flow imaging (CDFI).[13] As abdominal organs are important organs that sense and respond to ischemia and hypoxia, ultrasonic evaluation of abdominal organ function and blood flow in patients after cardiopulmonary bypass may comprehensively and effectively reflect the state of abdominal organ ischemia and hypoxia. Therefore, in this study, a semiquantitative score of abdominal organ blood flow and function was established, and the utility of this new score for predicting the duration of MV and clinical outcome was evaluated.

Methods

Participants and clinical data

Intensive care unit (ICU) patients who were hospitalized in Peking Union Medical College Hospital from March to July 2021 after a cardiopulmonary bypass were enrolled in the present study. The protocol was approved by the Ethics Committee of Peking Union Medical College Hospital (ethics code: ZS-1612). Prior to measurement, the patient's guardian signed an informed consent form. The inclusion criteria were as follows: (1) patients with cardiopulmonary bypass and (2) clear images were obtained by ultrasound of the gastric antrum, superior mesenteric artery, colon, and small intestine. The exclusion criteria were as follows: (1) history of abdominal trauma or abdominal surgery in the 6 weeks preceding hospital admission; (2) inflammatory intestinal disease; (3) chronic respiratory disease; (4) chronic renal insufficiency; and (5) postoperative pulmonary infection. All the relevant clinical data and experimental data were collected at the ICU admission and 12, 24 and 48 h after admission.

Assessment and measurements

Ultrasonography was used to count t_1 once at 0–12 h after ICU admission and to count t_2 at 12–24 h after the operation ICU admission. All ultrasonic measurements were made by two experienced ICU doctors (Longxiang Su and Chaofu Yue). There was a Critical Ultrasound Study Group (CCUSG) formal training certification, and qualifications were obtained after there was no significant difference between previous measurements made by the two doctors. All the measured images were checked and then stored for later analysis.

The ultrasonic examination was performed with a Mindray M9 ultrasonic diagnostic instrument (Mindray, Shenzhen, China) with a probe frequency of 5–10 MHz (just one machine, one abdominal probe). The examiners blindly examined the patients' gastric antrum, superior mesenteric artery, kidney, small intestine, and colon.

Gastric antrum examination

The patient was placed in the supine and right supine positions, and the long axis of the probe is set parallel to the patient's body. Beginning from the left inferior rib margin and the lateral side of the rectus abdominis, the probe is slowly moved to the right inferior costal margin, and the antrum diameter is measured after finding a clear image. Gastric antrum grading is as follows: Grade 0: with the patient lying in the supine and right supine positions, the gastric antrum is empty (Supplementary Figure S1A and B); Grade 1: with the patient lying in the right supine position, gastric juice is detected, indicating a small quantity of fluid (Supplementary Figure S1C and D); and Grade 2: gastric juice is detected in the gastric antrum when the patient is lying in the supine and right supine positions, indicating a large quantity of fluid (Supplementary Figure S1E and F).[14,15]

Superior mesenteric artery (SMA) examination

The patient was assumed supine position; beginning from the inferior margin of the right rib and the lateral edge of the rectus abdominis, the probe was moved below the xiphoid process to reveal the inferior vena cava, the long axis of the abdominal aorta, and finally the long axis of the SMA. The blood flow spectrum was measured by pulsed wave (PW) Doppler at 1–2 cm above the opening of the abdominal aorta and the superior mesenteric artery (Supplementary Figure S2).[16]

Small intestine and colon examination

The patient assumes was assumed horizontal position, and the probe is moved from the right iliac fossa horizontally and in parallel to the patient's body. Upon locating the colon, the probe direction is adjusted to reveal the longitudinal section of the colon; the widest or thickest part of the colon is located and measured. Beginning from the right iliac fossa again, the probe is moved horizontally and parallel to the patient's body while exerting a small amount of pressure, and the tail side to the head side is scanned again to locate the widest canal and the thickest wall of the small intestine. After the probe reaches the small intestine above the navel, the probe is then fixed, and the results are observed for 3 min to evaluate the peristalsis of the small intestine (Supplementary Figure S3).[9,17]

Renal blood flow

With the long axis of the left and right kidneys clearly displayed, the renal blood flow is semiquantitatively evaluated by CDFI: Grade 0: there is no blood flow throughout the entire kidney; Grade 1: a small quantity of blood flow is detected near the renal hilum; Grade 2: renal hilum and most interlobular blood flow can be detected; and Grade 3: blood flow in the arcuate artery can be detected (Supplementary Figure S4).

Table 1
Abdominal-visceral-blood-flow-and-function score.

Items	Score		
	0	1	2
Stomach*			
Grade	0	1	2
Small bowel			
Intestinal peristalsis	Yes	No	NA
Diameter (cm)	<2	≥2	NA
Thickness (mm)	1–3	3–6	>6, <1
Colon			
Diameter (cm)	<4	≥4	NA
Thickness (mm)	1–4	<4–6	>6, <1
SMA			
PSV (cm/s)	80–220	Abnormal	NA
RI	0.80–0.89	Abnormal	NA
Kidney			
Semiquantitative analysis	3	2	1/0 (no blood flow)

NA: Not available; PSV: Peak systolic velocity; RI: Resistance index; SMA: Superior mesenteric artery.
* Gastric grading (supplementary S1).

Abdominal-visceral-blood-flow-and-function score (AVBFS)

The results of ultrasound examination, which is currently used to evaluate GI function in critical care medicine, were combined with results for GI size, peristalsis, superior mesenteric artery blood flow, and renal perfusion to establish a scoring system for abdominal organ blood flow and function (Table 1).

Statistical methods

SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC, USA) was used for data analysis; the normally distributed measurement data are expressed as the mean±standard deviation and were compared by the *t*-test, data for non-normally distributed variables were expressed as the median or quartile, and the Mann–Whitney U test was used to perform a comparative analysis. There was a significant difference between the two sides (P <0.05). A multiple linear regression analysis was carried out on data obtained for groups with different duration of MV to evaluate the odds ratio of the AVBFS. A receiver operating characteristic curve (ROC) curve for the AVBFS was plotted, and the area under the ROC curve (AUC) was calculated to predict all-cause mortality. The Jordan index was used to determine the best criticality of the abovementioned variables.

Results

General demographics

Of the 92 patients who underwent cardiopulmonary bypass, 41 were finally included according to the inclusion and exclusion criteria, and the results are shown in Figure 1. There were 23 male patients, accounting for 56.1% of the actual enrolled patients (Table 2). The highest AVBFS score was 12, and the highest score of patients with cardiopulmonary bypass was 6.

Correlation analysis between scores and related indices

The AVBFS t_1 and t_2 were significantly correlated with the duration of MV, number of days spent in the ICU, APACHE-II score, SOFA score, and norepinephrine use time (P <0.05), but AVBFS t_1 and t_2 were not correlated with the Lactate levels. The AVBFS t_1 is correlated with the epinephrine use time, but AVBFS t_2 is not correlated, as shown in Table 3.

The predictive value of scores for the duration of MV

The duration of MV was significantly correlated with AVBFS t_1 and $t_{2,}$ APACHE-II (1) (at 24 h after ICU admission), and SOFA (2) (highest scores at 12-24 h after ICU admission), this indicated that it was correlated with the critical condition and organ damage of the patients. The patients with a duration of MV ≥36 h were assigned to late extubation group, and those with a duration of MV <36 h were assigned to early extubation group. The AVBFS, number of days spent in the ICU, APACHE-II (1), APACHE-II (2)(at 48 h after ICU admission), SOFA (2), epinephrine, and norepinephrine use for the later extubation group were significantly higher than early extubation group (P <0.05). There was no significant difference in SOFA (1) (highest scores within 12 h after ICU admission), lactate (1), (2), or (3) (at 0 h, 12 h, and 24 h after ICU admission) between the two groups (P >0.05) (Table 4).

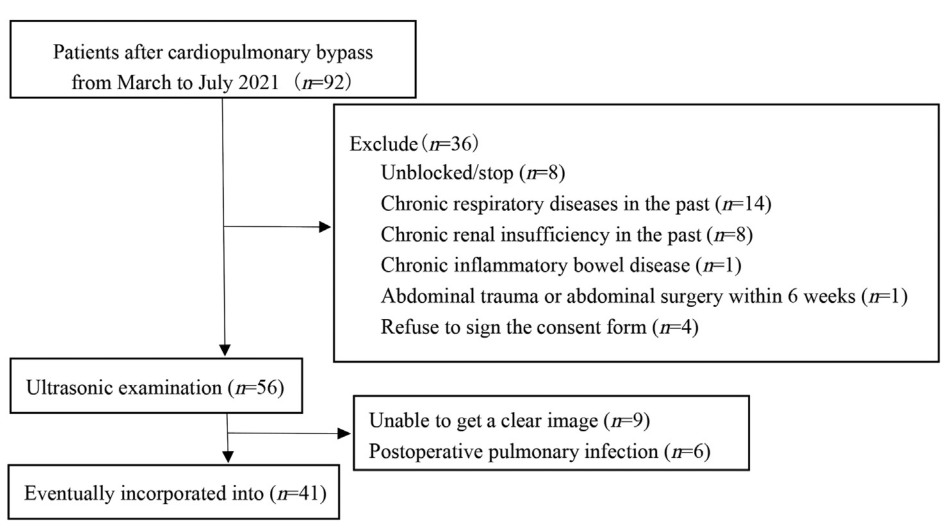

Figure 1. Inclusion and exclusion of patients.

Table 2
Baseline data of the enrolled patients (n=41)*.

Items	Data
Sex: male	23 (56.1)
Age (years)	56.1±12.5
Baseline circulation	
CVP (mmHg)	9.0±2.2
HR (beats/min)	89±11
SBP (mmHg)	138±19
DBP (mmHg)	72±12
MAP (mmHg)	93±13
Lactate (mmol/L)	6.01±3.43
$ScvO_2$	78.2±7.8
$Pcv\text{-}aCO_2$ (mmHg)	3.79±2.45
WBC (×10^9/L)	12.8±3.8
PCT (ng/mL)	0.32 (0.10-1.25)
T (°C)	36.11±0.45
Cardiopulmonary bypass time (min)	131±52
Aortic occlusion time (min)	90±47
Major disease	
Valvular disease	14 (34.1)
Aortic disease	7 (17.1)
Infectious disease	4 (9.8)
CABG	13 (31.7)
Atrial mass	1 (2.4)
HOCM	1 (2.4)
PTE	1 (2.4)

Data are presented as mean ± standard deviation, median(interquartile range) or n (%).
AVBFS: Abdominal-visceral-blood-flow-and-function score; CABG: Coronary artery bypass grafting; CVP: Central venous pressure; DBP: Diastolic blood pressure; HOCM: Hypertrophic obstructive cardiomyopathy; HR: Heart rate; MAP: Mean arterial pressure; PCT: Procalcitonin; $Pcv\text{-}aCO_2$: Arteriovenous carbon dioxide difference; PTE: Pulmonary thromboendarterectomy; $ScvO_2$: Systemic central venous oxygen saturation; SBP: Systolic blood pressure; T: Temperature; WBC: White blood cells.
* These basic data are the first values collected from the patient after ICU entrance.

All enrolled patients were divided into two groups: the improved group (AVBFS t_2-t_1 < 0) and the unimproved group (AVBFS t_2-t_1 ≥0). The patients in the improved group had better outcomes in duration of MV, length of ICU stay, epinephrine use and norepinephrine use, SOFA (2), and Lactate (1) (P <0.05) (Table 5).

Next, a multiple linear regression analysis was conducted on the data of patients with different duration of MV. The results were as follows: R^2=0.444, adjusted R^2=0.383, and Durbin–Watson=2.120. The histogram and normal P–P plot of the regression standardized residual indicated that the data followed a normal distribution. The results showed that AVBFS t_1 was a risk factor affecting recovery (Table 6).

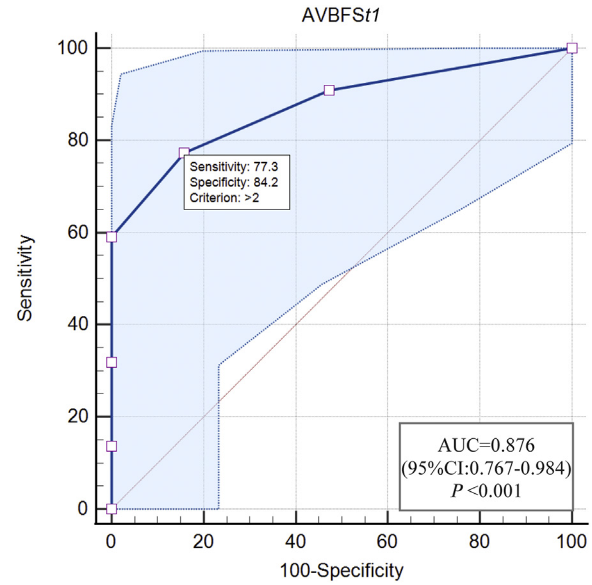

Figure 2. ROC curve of the diagnostic efficiency of AVBFS at 0–12 h after ICU admission (t_1).
AUC: Area under the ROC curve; AVBFS: Abdominal-visceral-blood-flow-and-function score; CI: Confidence interval; ROC: Receiver operating characteristic curve.

The predicted value of scores in longer duration of MV

The ROC curve was determined for the data of patients with different duration of MV (≥36 h and <36 h). The diagnostic efficiency determined by using the ROC curve was as follows: AUC=0.876 (95 % confidence interval [CI]: 0.767–0.984), cut-off value=2.5 points, specificity=0.842, and sensitivity=0.773 (Figure 2).

Table 3
Correlation of AVBFS at 0-12 h after ICU admission (t_1) and 12-24 h after the operation(t_2) with related parameters.

Items	AVBFS t_1		AVBFS t_2	
	Correlation coefficient	P-value	Correlation coefficient	P-value
Length of ICU stay	0.61	0.000	0.45	0.003
Duration of mechanical ventilation	0.62	0.000	0.50	0.001
APACHE-II (1)*	0.53	0.000	0.47	0.002
APACHE-II (2)*	0.71	0.000	0.47	0.002
SOFA (1)†	0.42	0.006	0.33	0.035
SOFA (2)†	0.68	0.000	0.56	0.000
Lactate (1)‡	0.01	0.947	0.02	0.868
Lactate (2)‡	0.22	0.158	0.18	0.240
Lactate (3)‡	0.28	0.069	0.30	0.056
Epinephrine use§	0.34	0.029	0.22	0.161
Norepinephrine use§	0.52	0.000	0.42	0.006

APACHE-II: Acute physiology and chronic health evaluation II; AVBFS: Abdominal-visceral-blood-flow-and-function score; ICU: Intensive care unit; SOFA: Sequential organ failure assessment.
* APACHE-II (1) and (2) were scored at 24 h and 48 h after ICU admission.
† SOFA (1) and (2) were the highest scores obtained within 12 h and 12–24 h after ICU admission respectively.
‡ Lactate (1), (2), and (3) were the lactate levels at 0 h, 12 h, and 24 h after ICU admission respectively.
§ The epinephrine and norepinephrine use times correspond to the total time of postoperative use of epinephrine and norepinephrine, respectively.

Table 4
Comparison of the results of two groups with different duration of mechanical ventilation.

Items	Late extubation group (n=22)	Early extubation group (n=19)	t	P-value
AVBFS t_1	3.72±1.51	1.63±0.76	5.45	0.000
AVBFS t_2	3.45±1.14	1.52±1.02	5.65	0.000
Length of ICU stay (days)	8.50±7.21	2.89±1.32	3.33	0.002
APACHE-II (1)	13.95±5.01	9.26±3.64	3.37	0.002
APACHE-II (2)	11.72±5.20	7.94±3.52	2.67	0.011
SOFA (1)	10.77±3.00	9.31±2.10	1.76	0.085
SOFA (2)	8.18±4.33	4.15±2.45	3.57	0.001
Lactate (1)	5.60±4.15	4.95±2.58	0.59	0.558
Lactate (2)	3.25±2.92	2.16±1.18	1.50	0.140
Lactate (3)	2.05±1.06	1.53±1.21	1.45	0.153
Epinephrine use (h)	27.45±36.38	8.78±10.10	2.16	0.037
Norepinephrine use (h)	50.18±41.85	6.47±9.18	4.45	0.000

Data are presented as mean±standard deviation.
APACHE-II: Acute physiology and chronic health evaluation II; AVBFS: Abdominal-visceral-blood-flow-and-function score; SOFA: Sequential organ failure assessment; t_1: at 0–12 h after ICU admission; t_2: at 12–24 h after ICU admission.

Table 5
Comparison of the results of two data points.

Items	Improved group (n=24)	Unimproved group (n=17)	t	P-value
Duration of mechanical ventilation (h)	27.04±14.19	118.05±112.51	17.31	0.000
Length of ICU stay (days)	3.41±1.63	9.41±8.00	10.08	0.003
APACHE-II (1)	11.04±4.76	12.82±5.23	0.12	0.721
APACHE-II (2)	7.20±5.04	12.29±6.90	1.67	0.203
SOFA (1)	10.12±2.17	10.05±3.38	3.07	0.087
SOFA (2)	4.91±2.93	8.29±4.72	8.07	0.007
Lactate (1)	4.62±2.54	6.26±4.41	7.86	0.008
Lactate (2)	2.13±1.21	3.61±3.17	3.67	0.063
Lactate (3)	1.56±1.09	2.15±1.17	1.10	0.299
Epinephrine use (h)	11.16±15.30	29.58±39.07	16.12	0.000
Norepinephrine use (h)	18.16±27.64	46.52±44.86	8.91	0.005

Data are presented as mean±standard deviation.
APACHE-II: Acute physiology and chronic health evaluation II; ICU: Intensive care unit; SOFA: Sequential organ failure assessment; t_1: at 0–12 h after ICU admission; t_2: at 12–24 h after ICU admission.

Table 6
Analysis of risk factors for delayed extubation.

Items	Unstandardized coefficients		Standardized coefficients	t	P-value	Collinearity statistics	
	β	Std. error	β			Tolerance	VIF
Constant	−60.23	28.23	NA	−2.13	0.040	NA	NA
AVBFS t_1	23.85	9.70	0.45	2.45	0.019	0.45	2.18
AVBFS t_2	8.72	9.94	0.14	0.87	0.386	0.53	1.86
APACHE-II (1)	3.90	2.61	0.22	1.49	0.145	0.65	1.52
SOFA (2)	−1.43	3.51	−0.06	−0.40	0.685	0.54	1.85

APACHE-II: Acute physiology and chronic health evaluation II; AVBFS: Abdominal-visceral-blood-flow-and-function score; NA: Not available; SOFA: Sequential organ failure assessment; t_1: at 0–12 h after ICU admission; t_2: at 12–24 h after ICU admission; VIF: Variance inflation factor.

Discussion

The AVBFS was significantly correlated with the duration of MV and the length of the ICU stay. The AVBFS of patients who required a ventilator ≥36 h was significantly higher than that of patients who required a ventilator <36 h. A multivariate linear regression analysis and the diagnostic efficiency results from the ROC curve for the data of patients with different duration of MV showed that the score for blood flow and function of abdominal organs at 0–12 h after operation had good predictive value for the duration of MV. A comparative analysis showed that there was no difference in the index of oxygen metabolism, lactic acid, and SOFA score within 0–12 h after entering the ICU between the two groups of patients with different duration of MV (≥36 h and <36 h).

These results show that the AVBFS can serve as an early predictor of common abdominal organ injury after cardiopulmonary bypass and is an independent predictor of duration of MV and clinical outcome. Therefore, an abdominal organ injury can be located using the AVBFS to determine whether gastric retention and intestinal creep are caused by abnormal blood flow in the superior mesenteric artery or other paralytic intestinal dysfunction after reperfusion injury or by the lack of perfusion caused by systemic circulation and not by a single factor related to the GI tract. Evaluating whether abnormal renal function is caused by renal perfusion can facilitate early intervention and improve the clinical outcome.

A key motivation for performing this study was that many previous studies have confirmed that acute renal injury is a risk factor affecting the clinical prognosis of patients with GI dysfunction caused by cardiopulmonary bypass in cardiac surgery, and complications of intestinal obstruction, GI bleeding, intestinal perforation, and mesenteric hemorrhage, in particular, significantly increased mortality.[18] Up to 30% of patients with cardiopulmonary bypass are affected by acute renal injury.[2] In addition to ischemia–reperfusion injury and insufficient organ perfusion, acute renal injury may also be caused by continuous, non-pulsating blood flow during cardiopulmonary bypass, activation of inflammatory cytokines caused by the operation, and functional anemia caused by dilution of prefilling fluid. Other reasons for acute renal injury include the decreased oxygen-carrying capacity of terminal organs.[19] The GI tract and respiratory system are closely linked, and any change in one system may have an impact on the other system. It is currently considered that the GI tract produces common mucosal immunity with the lung through the regulation of mucosal immunity, tolerance, and inflammatory disease susceptibility. Many respiratory diseases are closely related to intestinal flora disorders.[20,21] In addition, in the case of shock-reperfusion injury, enterogenic inflammatory products induce the activation of neutrophils and endothelial cells through mesenteric lymph nodes, which enhance the initiation of many important chemokines and promote the occurrence and development of lung injury.[22]

This study has some limitations. First, as a limited sample size was collected from a single center, the results cannot be extensively generalized. The inference of causality needs further exploration. Second, it is uncertain whether the current ultrasound study on liver and spleen blood flow can reflect adverse effects on the liver and spleen. Therefore, the abdominal organs for which the AVBFS are determined do not include the liver and spleen. Third, the gastric antrum method is used to evaluate the gastric volume, and the CDFI semiquantitative evaluation of the renal blood flow is not quantitative. Fourth, the proposed score can only be applied to evaluate the GI organs of patients with cardiopulmonary bypass and cannot be applied to patients with dysfunction or risk of failure of other abdominal organs. The aforementioned factors should be considered in a follow-up study to improve the predictive role of the AVBFS.

Conclusions

AVBFS is a noninvasive, effective, and timely evaluation method. The correlation of the celiac visceral blood flow and function score with APACHE-II, SOFA, epinephrine, and norepinephrine use. It is related to early and late extubation after cardiac surgery. This study indicated that the sample size collected is very small and is designed by a single center. We will grade the value of the score through a multicenter large-sample study in the future.

Author Contributions

Yun Long and Huaiwu He substantially contributed to the experimental conception and design. **Jun Wang, Na Cui, Yuankai Zhou, Wei Cheng, Bo Tang and Xi Rui** contributed to the acquisition of data or analysis of data. **Chaofu Yue and Longxiang Su** were responsible for manuscript writing.

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Ethics Statement

The study obtained the approval of the Institutional Research and Ethics Committee of the Peking Union Medical College Hospital for human subjects (ZS-1612).

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jointm.2023.09.001.

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