Heart Surgery Forum 2023; 26(3): E234–E239 https://journal.hsforum.com/
doi: 10.1532/hsf.5465

Article

Comparison of Carotid Blood Flow Measured by Ultrasound and Cardiac Output in Patients Undergoing Cardiac Surgery

Xin-yi Bu[1,†], Jian-kai Wang[2,†], Yong Zhang[1], Li-hai Chen[1], Jia-cong Liu[1], Ya-mei Zhao[1], Hong-wei Shi[1], Ya-li Ge[1,*]

[1]Department of Anesthesiology, Nanjing First Hospital, Nanjing Medical University, 210029 Nanjing, Jiangsu, China
[2]Department of Cardiothoracic and vascular surgery, Nanjing First Hospital, Nanjing Medical University, 210029 Nanjing, Jiangsu, China
*Correspondence: ge_yl@163.com (Ya-li Ge)
[†]These authors contributed equally.

Submitted: 18 January 2023 Revised: 28 February 2023 Accepted: 3 March 2023 Published: 31 May 2023

Abstract

Background: In general, cerebral blood flow accounts for 10–15% of cardiac output (CO), of which about 75% is delivered through the carotid arteries. Hence, if carotid blood flow (CBF) is constantly proportional to CO with high reproducibility and reliability, it would be of great value to measure CBF as an alternative to CO. The aim of this study was to investigate the direct correlation between CBF and CO. We hypothesized that measurement of CBF could be a good substitute for CO, even under more extreme hemodynamic conditions, for a wider range of critically ill patients. **Methods**: Patients aged 65–80 years, undergoing elective cardiac surgery were included in this study. CBF in different cardiac cycles were measured by ultrasound: systolic carotid blood flow (SCF), diastolic carotid blood flow (DCF), and total (systolic and diastolic) carotid blood flow (TCF). CO simultaneously was measured by transesophageal echocardiography. **Results**: For all patients, the correlation coefficients between SCF and CO, TCF and CO were 0.45 and 0.30, respectively, which were statistically significant, but not between DCF and CO. There was no significant correlation between either SCF, TCF or DCF and CO, when CO was <3.5 L/min. **Conclusions**: Systolic carotid blood flow may be used as a better index to replace CO. However, the method of direct measurement of CO is essential when the patient's heart function is poor.

Keywords

carotid artery; cardiac output; cardiac surgery; carotid ultrasound; transesophageal echocardiograph

Introduction

The monitoring and evaluation of cardiac output (CO) is of great significance in diagnosis and management of diseases, especially in critically ill patients with rapid hemodynamic changes. Pulmonary artery catheterization is normally utilized for CO measurement, but this invasive procedure can cause multiple complications and is required to be performed by trained physicians. Transthoracic echocardiography (TTE) is another method that can safely and effectively monitor CO and hemodynamics. However, TTE is not always available because of poor patient positioning or surgical incisions. Similarly, transesophageal echocardiography (TEE) for assessing CO also has limitations, such as requirement for general anesthesia. Thus, it is challenging to monitor CO.

In general, cerebral blood flow accounts for 10–15% of CO [1,2], of which about 75% is delivered through the carotid arteries, while the remaining 25% is delivered through the vertebral arteries [3,4]. Hence, if carotid blood flow (CBF) is constantly proportional to CO with high reproducibility and reliability, it would be of great value to measure CBF as an alternative to CO.

However, the relationship between CBF and CO is controversial, with very few studies and limited data. Some studies suggested that CBF could be used to predict volume responsiveness and increased CO led to an increase in CBF [5], while others suggested that there was no correlation or even negative correlation between CBF and CO [6].

Therefore, the objective of this study was to investigate the direct correlation between CBF and CO. We hypothesized that measurement of CBF could be a good substitute for CO, even under more extreme hemodynamic conditions, for a wider range of critically ill patients. We proposed to test its reproducibility and robustness stability in patients undergoing cardiac surgery.

Methods

Patients: This was an observational study conducted from March 2022 to October 2022. The study was reviewed and approved by the Ethics Committee. All patients signed written informed consent and agreed to follow up. Inclusion, exclusion, and withdrawal criteria of the study were as follows: (1) Inclusion criteria: Patients aged 65–80 years, scheduled for elective cardiac surgery. (2) Exclusion criteria: History of neck surgery or trauma, peripheral vascular disease, body mass index (BMI) >30 kg/m^2, carotid stenosis >50%, neurological diseases affecting CBF: history of cerebrovascular disease, dementia, epilepsy and stroke, patients with non-sinus rhythm, aortic valve insufficiency (moderate or severe). (3) Withdrawal criteria: Patients with new stenosis and plaque found by carotid ultrasound.

Research parameters: CBF and CO were measured by ultrasound and TEE, respectively, after induction of anesthesia (measurement time point was before the start of operation, and hemodynamics were stable for at least 60 s during measurements).

Independence and simultaneity of measurements: CBF and CO measurements independently and simultaneously were performed by two experienced physicians. All ultrasound indexes were the average values of three consecutive complete cardiac cycles.

Measurement of CBF by ultrasound: The patient was placed in the supine position, with full exposure of neck and head towards the contralateral side. A linear array transducer (Philips ultrasound, Bothell, WA, USA, CX50 Diagnostic ultrasound system) was placed on the patient's left neck, and the carotid artery was positioned in the center of the screen, after excluding the new onset stenosis and plaque in cross-section. The probe was then rotated 90° to obtain a satisfactory long-axis image of the carotid artery, and the maximum diameter of the vessel was displayed by adjusting the acoustic beam. The inner diameter of carotid artery and Doppler blood flow parameters were measured at the level of the lower border of the thyroid cartilage and 2 cm proximal to the carotid bifurcation.

Measurement of Doppler blood flow parameters: The Doppler sampling line was placed in the center of the vessel, and the sampling direction was approximately parallel to the vessel direction, with the Doppler angle maintained between 45° and 60°. The sampling volume was adjusted by 1 mm, and the spectral Doppler scale was set low enough to fill the available space without aliasing. The image was frozen after it was full on the screen. The instrument's built-in software sketched and measured the systolic velocity time integral (VTIs), diastolic velocity time integral (VTId), and total (systolic and diastolic) velocity time integrals (VTIt) (Fig. 1).

Measurement of internal diameter of carotid artery: The inner diameter of the blood vessel was measured at the sampling volume site. The endovascular diameter, determined as the vertical distance between the endovascular lines, was measured at end-systole (Ds), and end-diastole (Dd) and total systolic and diastolic (Dt), Dt = (Ds + Dd)/2.

Calculation of CBF: The cross-sectional area of the carotid artery was assumed to be circular. CBF was derived from the cross-sectional area of the vessel and the velocity time integral (VTI).

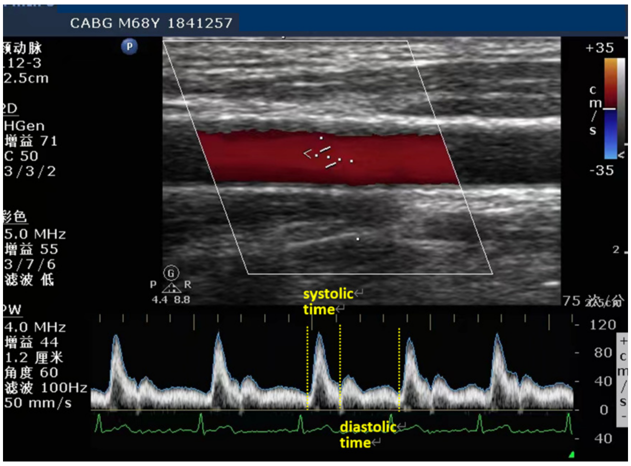

Fig. 1. Measurement of CBF by ultrasound.

Table 1. Patients' characteristics, carotid blood flow and cardiac output.

	N	Value
Age, y	100	70.50 ± 5.24
Weight, kg	100	67.94 ± 6.17
Height, m	100	1.68 ± 0.08
Male/Female, n	100	69/31
BMI, kg/m^2	100	23.90 ± 2.78
SCF, L/min	100	0.40 [0.28–0.55]
DCF, L/min	100	0.29 [0.20–0.42]
TCF, L/min	100	0.73 [0.50–0.93]
CO, L/min	100	4.18 ± 1.21

BMI, body mass index; SCF, systolic carotid blood flow; DCF, diastolic carotid blood flow; TCF, total (systolic and diastolic) carotid blood flow; CO, cardiac output. Values are median [IQR], count or mean ± SD.

$$\text{Systolic carotid blood flow (SCF)} = \pi Ds^2 \times VTIs \times HR/4$$
$$\text{Diastolic carotid blood flow (DCF)} = \pi Dd^2 \times VTId \times HR/4$$
$$\text{Total carotid blood flow (TCF)} = \pi Dt^2 \times VTIt \times HR/4$$

Measurement of CO: CO measurement simultaneously was performed by the other doctor through TEE. The velocity time integral (VTI) of the left ventricular outflow tract (LVOT) was measured in the deep transgastric left ventricular long-axis view, and the diameter of the LVOT (D) was measured in the mid-esophageal LVOT view.

$$CO = \pi D^2 \times VTI \times HR/4$$

Statistical analyses: SPSS 19.0 statistical software (IBM Corp., Chicago, IL, USA) was used for data analysis. Normally distributed continuous variables were expressed as mean ± standard deviation ($\bar{x} \pm s$), and independent samples t-test was used for comparison between groups. Non–

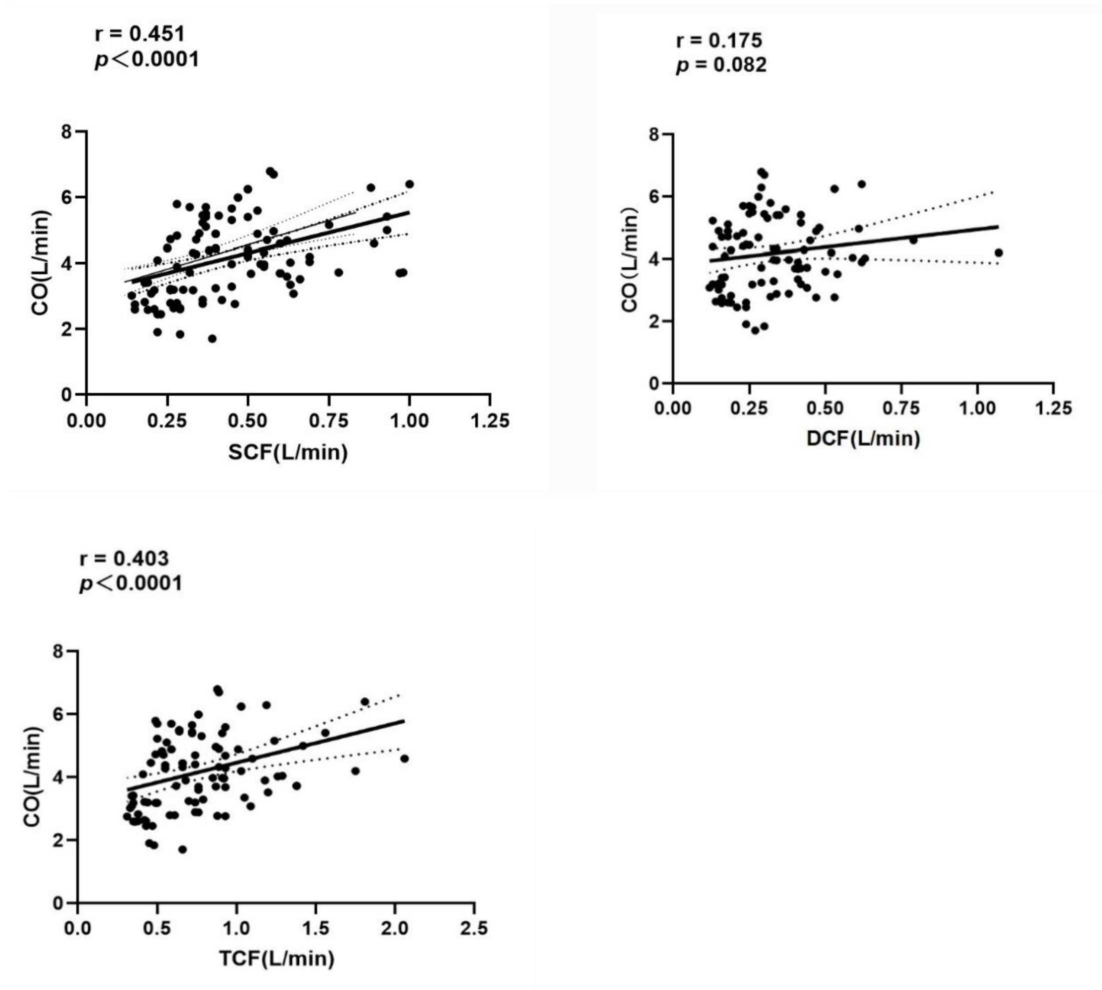

Fig. 2. Correlation between SCF, DCF, TCF, and CO for all patients (N = 100, 100, and 100, respectively).

normally distributed variables were expressed as median (M) and interquartile range (IQR), and the rank sum test was used for comparison between groups. The count data were expressed as cases (%), and the Fisher exact probability method and χ^2 test were used for comparison between groups. Scatter plots of SCF, DCF, TCF, and CO were established, respectively, and the correlation coefficients were analyzed among them. When patients were in extreme hemodynamic condition CO <3.5 L/min, the correlation between corresponding SCF, DCF, TCF, and CO was statistically analyzed. $p < 0.05$ was considered statistically significant.

Results

Patient characteristics: A total of 100 patients were included in this study. Table 1 shows the patients' characteristics, CBF, and CO (Table 1).

Correlation between CBF and CO: Fig. 2 shows that the correlation coefficients between SCF, DCF, TCF and CO were 0.451 ($p < 0.0001$), 0.175 ($p > 0.05$), and 0.403 ($p < 0.0001$), respectively, for all patients (Fig. 2).

For CO <3.5 L/min: Among the 100 patients, 32 had CO <3.5 L/min. Fig. 3 shows that the correlation coefficients between SCF, DCF, TCF, and CO were 0.283 ($p > 0.05$), –0.130 ($p > 0.05$), and 0.156 ($p > 0.05$), respectively, when CO <3.5 L/min (Fig. 3).

Discussion

This study showed a significant correlation between CBF measured by ultrasound and CO measured by TEE. The correlation coefficients between SCF and CO, and TCF and CO were statistically significant, but not between DCF and CO. There was no significant correlation between either SCF, TCF or DCF and CO when CO was <3.5 L/min. It suggests that SCF is a good alternative to CO in patients with preserved CO (≥3.5 L/min).

Whether the measurement of CBF can be used as a substitute for CO remains controversial. Weber *et al*. [7] compared the correlation between CBF and cardiac index (CI) in 11 healthy volunteers and found weak or no correla-

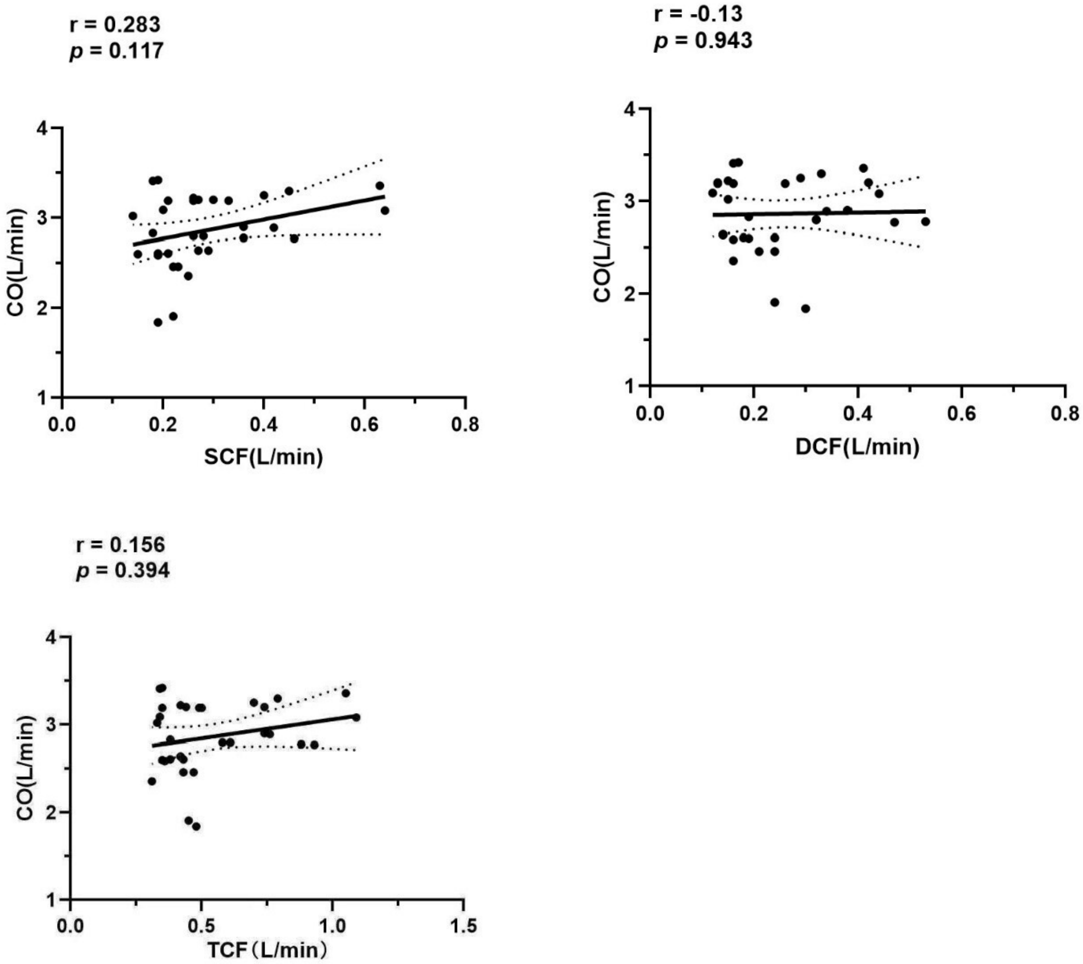

Fig. 3. The correlation between SCF, DCF, TCF and CO when CO <3.5 L/min (*N* = 32, 32 and 32, respectively).

tion. Moreover, they found a negative correlation between CBF and CI in 25 patients with normal CI before and after cardiac surgery [6]. According to them, although most CO is delivered to the brain through the carotid artery, CBF is strictly regulated, and changes in CO do not necessarily lead to proportional changes in CBF, which is highly unpredictable and variable. Lassen found that CBF displayed an autonomic regulation function under normal conditions (MAP between 50–150 mmHg), resulting in relatively stable CBF [8]. However, different views recently have been proposed. Skytioti *et al.* [9] reported that the internal carotid blood flow (ICBF) was correlated with the changes in CO in healthy and awake people, even if the MAP remained unchanged. Olesen *et al.* [10] found that under a stable level of anesthesia, an increase in MAP from 60–65 to 80–85 mmHg increases ICBF by 15%. An increase in MAP from 60–65 to 70–75 mmHg increased ICBF by 7%, and a further increase in MAP to 80–85 mmHg increased ICBF by 8% [10]. These findings were in contrast to the classical autonomic brain regulation.

Other scholars had suggested that CBF can be a substitute for CO. Skytioti *et al.* [11] studied the process from waking state to anesthesia, pneumoperitoneum and head elevation head-up position in ASA class I–II patients undergoing elective laparoscopic surgery. It was found that a decrease in CI of 1 L/min/m^2 predicted a decrease in ICBF of 88 mL/min. The authors suggested that the significant decrease in ICBF was related to the decrease in CO. In addition, a strong correlation of 0.96 (close to 1) between CBF measured by ultrasound and CO measured by TTE was reported by Fazelinejad *et al.* [12].

All the above studies used total (systolic and diastolic) CBF to compare with CO. Sidor *et al.* [13] emphasized the importance of using systolic carotid blood flow (SCF). The authors believed that diastolic carotid blood flow (DCF) was less dependent on stroke volume. It was the result of the kinetic energy, inertia of the heart to the blood stream, and the reflex of aortic valve closure in early diastole. These may account for the different results of the current study, which needs more research.

Peng *et al*. [14] enrolled 148 ICU patients with different primary diseases and compared the correlation between CBF and CO, showing a correlation coefficient of 0.537. However, in patients with septic shock, multiple trauma and respiratory failure, the correlation coefficients between CBF and CO were low, due to the small sample sizes. In a group of 34 critically ill patients, Marik *et al*. [5] measured CBF to assess fluid responsiveness induced by passive leg raising and observed a 25% increase in stroke volume index and a 79% increase in CBF. Our results showed no significant correlation between SCF, DCF, TCF, and CO when CO <3.5 L/min, indicating it is more accurate to measure cardiac function directly for patients with poor cardiac function, and it is not suitable to estimate CO by CBF.

Previous studies assumed that the internal diameter of the carotid artery was constant and only the effect of VTI on blood flow was considered. However, changes in CBF are partly due to changes in VTI, as well as carotid internal diameter, so carotid arteries should not be considered as rigid vessels [11]. In this study, Ds, Dd, and Dt in different cardiac cycles were studied to avoid the influence of internal diameter alterations on the results. Moreover, the correlation between SCF, DCF, TCF, and CO was analyzed, respectively, which increased the accuracy of the study.

This study had some limitations. First, only left CBF data were obtained in this study because a CVP catheter was placed in the right side of the patient. However, we also considered that in most patients, the right carotid artery originates from the brachiocephalic artery and the left carotid artery originates directly from the aorta.

Conclusions

There was a significant correlation between CBF measured by ultrasound and CO measured by TEE. The correlation between systolic carotid blood flow and CO is more obvious. Systolic carotid blood flow may be used as a better index to replace CO. However, the method of direct measurement of CO is essential when the patient's heart function is poor. It is hoped that in the future, continuous ultrasound monitoring of CBF can provide more ideas for the diagnosis and treatment of patients.

Availability of Data and Materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Study conception and design: XB, JW, YG. Data analysis: YoZ, LC. Data interpretation: LC, JL, YaZ, HS. Data collection: XB, JL. Drafting of the manuscript: XB, JW. Revisions to the manuscript: XB, JW, YoZ, LC, JL, YaZ, HS, YG. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The research described has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. The study was approved by the Ethics Committee of Nanjing First Hospital (No. KY20210204-01). All patients signed written informed consent and privacy rights always be observed.

Acknowledgment

The authors thank the members of the Department of Ultrasound for their contributions and discussions during the preparation of this manuscript.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Zwiebel WJ, Pellerito JS. Introduction to vascular ultrasonography (pp. 61–89). 5th edn. Elsevier Saunders: Philadelphia. 2004.

[2] Jain V, Langham MC, Wehrli FW. MRI estimation of global brain oxygen consumption rate. Journal of Cerebral Blood Flow and Metabolism. 2010; 30: 1598–1607.

[3] Albayrak R, Degirmenci B, Acar M, Haktanir A, Colbay M, Yaman M. Doppler sonography evaluation of flow velocity and volume of the extracranial internal carotid and vertebral arteries in healthy adults. Journal of Clinical Ultrasound. 2007; 35: 27–33.

[4] Scheel P, Ruge C, Petruch UR, Schöning M. Color duplex measurement of cerebral blood flow volume in healthy adults. Stroke. 2000; 31: 147–150.

[5] Marik PE, Levitov A, Young A, Andrews L. The use of bioreactance and carotid Doppler to determine volume responsiveness and blood flow redistribution following passive leg raising in hemodynamically unstable patients. Chest. 2013; 143: 364–370.

[6] Weber U, Glassford NJ, Eastwood GM, Bellomo R, Hilton AK. A Pilot Assessment of Carotid and Brachial Artery Blood Flow Estimation Using Ultrasound Doppler in Cardiac Surgery Pa-

tients. Journal of Cardiothoracic and Vascular Anesthesia. 2016; 30: 141–148.
[7] Weber U, Glassford NJ, Eastwood GM, Bellomo R, Hilton AK. A pilot study of the relationship between Doppler-estimated carotid and brachial artery flow and cardiac index. Anaesthesia. 2015; 70: 1140–1147.
[8] LASSEN NA. Cerebral blood flow and oxygen consumption in man. Physiological Reviews. 1959; 39: 183–238.
[9] Skytioti M, Søvik S, Elstad M. Internal carotid artery blood flow in healthy awake subjects is reduced by simulated hypovolemia and noninvasive mechanical ventilation. Physiological Reports. 2016; 4: e12969.
[10] Olesen ND, Frederiksen HJ, Storkholm JH, Hansen CP, Svendsen LB, Olsen NV, *et al*. Internal carotid artery blood flow is enhanced by elevating blood pressure during combined propofol-remifentanil and thoracic epidural anaesthesia: A randomised cross-over trial. European Journal of Anaesthesiology. 2020; 37: 482–490.
[11] Skytioti M, Elstad M, Søvik S. Internal Carotid Artery Blood Flow Response to Anesthesia, Pneumoperitoneum, and Head-up Tilt during Laparoscopic Cholecystectomy. Anesthesiology. 2019; 131: 512–520.
[12] Fazelinejad Z, Hanafi MG, Amiripebdani F, Mosavi A. Comparison of cardiac output measured by carotid artery Doppler ultrasound and echocardiography in patients admitted to Golestan and Imam Khomeyni Hospitalsl in Ahvaz. Journal of Family Medicine and Primary Care. 2020; 9: 3304–3307.
[13] Sidor M, Premachandra L, Hanna B, Nair N, Misra A. Carotid Flow as a Surrogate for Cardiac Output Measurement in Hemodynamically Stable Participants. Journal of Intensive Care Medicine. 2020; 35: 650–655.
[14] Peng QY, Zhang LN, Ai ML, Li L, Hu CH, Zhang YX, *et al*. Common Carotid Artery Sonography Versus Transthoracic Echocardiography for Cardiac Output Measurements in Intensive Care Unit Patients. Journal of Ultrasound in Medicine. 2017; 36: 1793–1799.