Feasibility of common carotid artery point of care ultrasound in cardiac output measurements compared to invasive methods

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Abstract

Background Cardiac output (CO) measurement in the intensive care unit (ICU) requires invasive devices such as the pulmonary artery (PA) catheter or arterial waveform pulse contour analysis (PCA). This study tests the accuracy and feasibility of point of care ultrasound (POCUS) of the common carotid artery to estimate the CO non-invasively and compare it to existing invasive CO measurement modalities.

Methods Patients admitted to the surgical and cardiothoracic ICU in a tertiary university-affiliated academic center during a 4-month period, with invasive hemodynamic monitoring devices for management, were included in this cohort study. Common carotid artery POCUS was performed to measure the CO and the results were compared to an invasive device.

Results Intensivists and ICU fellows, using ultrasound of the common carotid artery, obtained the CO measurements. Images of the Doppler flow and volume were obtained at the level of the thyroid gland. Concurrent CO measured via invasive devices was recorded. The patient cohort comprised 36 patients; 52 % were females. The average age was 59 ± 13 years, and 66 % were monitored via PCA device and 33 % via PA catheter. Intraclass correlation coefficient (ICC) analysis demonstrated almost perfect correlation (0.8152) between measurements of CO via

ultrasound vs. invasive modalities. The ICC between POCUS and the invasive measurement via PCA was 0.84 and via PA catheter 0.74, showing substantial agreement between the ultrasound and both invasive modalities.

Conclusions Common carotid artery POCUS offers a non-invasive method of measuring the CO in the critically ill population.

Keywords Cardiac output · Ultrasound · Carotid doppler · Pulmonary artery catheter · Pulse contour analysis · Point of care ultrasound

Abstract

Background La misurazione della gittata cardiaca (CO) in Unità di Terapia Intensiva (ICU) richiede dispositivi invasivi come il cateterismo dell'arteria polmonare (PA) o l'analisi dell'onda dell'impulso arterioso (PCA). Questo studio si propone di valutare l'accuratezza e la fattibilità dell'ecografia (POCUS) della carotide comune per stimare la CO in modo non invasivo e confrontarla con le modalità esistenti di misurazione della CO effettuate in maniera invasiva.

Metodi I pazienti ricoverati in terapia intensiva chirurgica e cardiotoracica in un centro accademico, affiliato con l'università, nel corso di un periodo di quattro mesi, sottoposti a dispositivi di monitoraggio emodinamico invasivo sono stati inclusi in questo studio. E' stata eseguita l'ecografia dell'arteria carotide comune per misurare la CO ed i risultati sono stati confrontati con una tecnica invasiva.

Risultati Medici di terapia intensiva e borsisti, utilizzando l'ecografia della carotide comune, hanno ottenuto le misurazioni della CO. Immagini del flusso Doppler e di volume sono state ottenute a livello della ghiandola tiroidea. Contemporaneamente è stata registrata la CO mediante dispositivi invasivi. Il gruppo era costituito da 36

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pazienti; Il 52 % erano femmine. L'età media era di 59 ± 13 anni, e il 66 % sono stati monitorati tramite dispositivo PCA e il 33 % tramite catetere PA. L'analisi del coefficiente di correlazione (ICC) ha dimostrato la correlazione quasi perfetta (0,8152) tra le misurazioni della CO con gli ultrasuoni e quelle con modalità invasive. Il ICC tra POCUS e la misurazione invasiva tramite PCA era 0,84 e catetere della PA era 0,74 mostrando sostanziale accordo tra l'ecografia e entrambe le modalità invasive.

Conclusioni La POCUS dell'arteria carotide comune offre un metodo non invasivo per misurare la CO nel paziente critico.

Introduction

Over the last two decades, hemodynamic monitoring and CO measurements in the ICU have been trending toward less invasive methods. In the early 1970s, we were introduced to the PA catheter. Its use has been in decline over the last 20 years, due to inherited risks of invasive procedures and limitations [1–3]. Newer less invasive methods are becoming available, such as the arterial waveform PCA, which has become very common in many ICUs across the globe.

POCUS has been gaining popularity in the ICU after it has provided an important diagnostic and therapeutic adjunct in the emergency department for the last two decades [4, 5]. One of the applications of POCUS is the limited echocardiogram where flow velocity through the left ventricular outflow tract is used to estimate the CO [6]. Despite its reproducibility, the operator can face many challenges in the ICU when dealing with suboptimal cardiac windows due to patient positioning difficulty, interfering incisions, wound dressings or body habitus.

Our hypothesis is that the common carotid artery is most often accessible for examination with POCUS and a calculation based on flow velocity and volume could be deduced to estimate the CO. Doppler measurement of the carotid artery is done routinely to examine the vessel patency and exclude narrowing. Using flow velocity and flow volume of a vessel can help identify arterial stenosis and disease [7–9]. The Doppler flow volume can measure the amount of blood passing through a vessel. Physiology studies quote a range of 15–26 % for the proportion of CO that is dedicated to cerebral perfusion. This range encompasses all patients from neonates to adults, stressed and non-stressed patients [7, 10, 11]. We hypothesize that the common carotid artery flow and volume can similarly represent an estimate of the CO. This study was designed to test the accuracy, efficiency and feasibility of carotid artery ultrasound analysis in comparison to the existing invasive CO measurement modalities.

Materials and methods

This study was conducted in a single urban tertiary care academic center. The institutional review board of the hospital approved the research for a prospective observational cohort study. Patients enrolled were from the surgical or cardiothoracic ICU. All patients had an existing invasive monitoring device, either a PA catheter or PCA, which was placed for hemodynamic monitoring and management based on a decision made by the primary treating ICU physician. Measurements were conducted with two examiners per patient; one physician obtained a cardiac output measure by the existing indwelling device and blinded the device to the physician obtaining the ultrasound images. Physicians obtaining the common carotid artery Doppler measurements were experienced in POCUS in the intensive care setting. All patients were placed in the semi-fowler position at 30° with the head of the patient rotated away from the ultrasound operator. Using the SonoSite edge ultrasound machine with a linear 38xi transducer 10 MHz (Seattle, WA), images of the common carotid artery were obtained at the level of the thyroid gland. The intraluminal common carotid artery diameter was measured in cross section and confirmed in longitudinal views

Fig. 1 **a** Position of the linear ultrasound transducer at the level of the thyroid gland in a cross-sectional orientation to measure the common carotid artery diameter (displayed in the *small box*). **b** Position of the linear ultrasound transducer at the level of the thyroid gland in a longitudinal orientation with the application of the color flow and Doppler to measure the flow volume (displayed in the *small box*)

(Fig. 1a). Carotid Doppler waveforms and the time average velocity of three to five cardiac cycles were obtained using a 1 mm caliper placed parallel to the vessel walls in the center of the laminar flow identified by the color flow ultrasound (Fig. 1b). The volume flow was calculated by the formula:

Volume flow = Cross-sectional diameter $\times$ Time average velocity.

Physiology studies quote a range of 15–26 % for the proportion of CO that is dedicated to cerebral perfusion [10, 11]. It was difficult to interpret the exact value to use when calculating the proportion of CO traveling through each carotid artery. Our working hypothesis was that cerebral flow comprised 20 % of resting CO via the carotid arteries. We based our estimate on Sato et al.'s [11] study, which stated that 80 % of cerebral perfusion was supplied via the carotid arteries, 40 % via each carotid artery and suggested that anywhere from 9 to 13 % of the CO would traverse each carotid artery depending on the degree of patient stress. We generalized this to 10 % and calculated the CO as follows:

$$\text{CO} = \text{Carotid Doppler flow volume} \times 10.$$

The operators obtaining the Doppler flow measurements and completing the calculations were blinded to the CO measured by the PA catheter or the PCA device. Concurrent vital signs and measured CO via invasive devices were recorded at the time that ultrasound imaging was obtained.

Exclusion criteria were patients less than 18 years old and pregnant patients. Those with any suspicion or evidence of increased intracranial pressure such as traumatic brain injury (TBI) or those with acute stroke were also excluded from the study to eliminate any potential interference from cerebral auto-regulation in our standard calculation. Our study was not powered to answer such questions. Volumetric quantitative measurements were not performed in patients with a stenosis of more than 50 % of any of the vessels examined and were also excluded due to the limitations in our sample size for this pilot study, and the low number of patients with significant atherosclerotic disease or stenosis at the mid common carotid artery that were found.

Analyses were performed using SAS 9.2. The level of statistical significance was set at a p value ≤ 0.05 . A paired t test was used to determine if there was a statistically significant difference between invasive CO and POCUS CO. A non-parametric version of the paired t test, the Wilcoxon signed-rank test, was used when looking within the levels of each variable (male, female, right carotid, left carotid, age group, etc.), due to the smaller sample size in each level. The intraclass correlation coefficient (ICC) was calculated for the comparison of invasive CO and ultrasound CO, overall and within each invasive modality. The ICC is a measure of reliability of the outcomes and

Table 1 Descriptive statistics, displayed as mean $\pm$ SD (Min, Max) for continuous variables and N (%) for categorical variables

Variable	Level	Mean $\pm$ SD (Min, Max) or N (%)
Invasive CO	L/min	7.09 $\pm$ 1.84 (3.60, 12.30)
Ultrasound CO	L/min	6.86 $\pm$ 2.11 (3.15, 15.10)
Difference in CO (invasive – ultrasound)	L/min	0.23 $\pm$ 1.20 (–2.80, 3.82)
Carotid artery	Left	27 (75.00)
	Right	9 (25.00)
Gender	Male	17 (47.22)
	Female	19 (52.78)
Age	Years	59.58 $\pm$ 13.48 (17.00, 78.00)
Age group	<50	6 (16.67)
	50–59	5 (13.89)
	60–69	18 (50.00)
	70–80	7 (19.44)
PCA or PA catheter	PCA	24 (66.67)
	PA catheter	12 (33.33)
Mechanical ventilation	No	24 (66.67)
	Yes	12 (33.33)

SD standard deviation, N number, CO cardiac output, PA pulmonary artery, PCA pulse contour analysis

indicates whether or not there is strong correlation between values within the levels.

Results

The cohort comprised 36 patients; 47 % were males, with an average age for the cohort of 59 ± 13 years. 66 % of patients were monitored via the PCA device and 33 % via PA catheter. 75 % of measurements were obtained from ultrasound study of the left common carotid artery. 33 % of patients were on mechanical ventilation support. Descriptive statistics are shown in Table 1. They are displayed as mean $\pm$ SD (Min, Max) for continuous variables and N (%) for categorical variables. A paired t test was performed to determine if there was a statistical difference between ultrasound and invasive means of monitoring cardiac output. The p value was 0.2629, suggesting that there was no difference in the method by which cardiac output was measured. This prompted a Wilcoxon signed-rank test analysis to determine the degree with which the two techniques correlated, defined as the intraclass correlation (ICC). The ICC analysis demonstrated almost perfect correlation (0.8152) between measurements of CO via ultrasound versus both invasive modalities (Tables 2 and 3). Age was not a significant discerning factor with ICC ranging 0.75–0.99 for

Table 2 Intra-class correlation coefficient (ICC), and its interpretation of the agreement levels between the two variables, (invasive vs. ultrasound cardiac output)

ICC	Interpretation
<0	Poor agreement
0.01–0.20	Slight agreement
0.21–0.40	Fair agreement
0.41–0.60	Moderate agreement
0.61–0.80	Substantial agreement
0.81–1.00	Almost perfect agreement

50 years and above. The ICC with POCUS for the invasive measurements via PCA was 0.84, and for the PA catheter 0.74 showing substantial agreement between POCUS and invasive modalities. There was no statistically significant difference in CO in patients who were on mechanical ventilation, when it was measured via POCUS or invasive techniques; $p = 0.6030$.

Results of the paired t test and Wilcoxon signed-rank tests are shown in Table 3. These are calculated overall (paired) and within each level (Wilcoxon), to identify if invasive CO is significantly different from POCUS CO, on average. The ICCs are also displayed in Table 2. This provides a value on the level of agreement between the two paired CO measurements and gives the corresponding interpretation of the agreement value. Based on these results, it appears that, overall, there is no statistically significant difference in the two CO measures ($p = 0.2629$). Our original hypothesis was to estimate the CO by multiplying the flow volume in either common carotid artery by the number ten (since it is equal to 10 % of the CO), and the results showed that the CO measured by POCUS of the common carotid artery was almost equal to 9.7 %. According to the ICC, when looking at the data overall, there appears to be almost perfect agreement between the two measures of CO (ICC = 0.8152). This suggests that, overall, POCUS CO measurements are reliable. Figure 2a, b displays these results.

CO measurements using ultrasound were also compared between the right and left carotid arteries, male and female, different age groups, PCA and PA catheter, and mechanical ventilation versus spontaneous breathing. The differences between invasive CO and POCUS CO were calculated (invasive – ultrasound), and these differences were used to analyze the relationships (comparing the CO differences in males to those in females). There were no statistically significant results from these analyses, implying that there was no situation where one level was significantly different than the other with respect to their differences in CO (Table 4).

Looking within specified levels, it appears that the average difference between the invasive CO and POCUS CO is statistically significant within the female group, 70-

to 80-year-old age group and the PCA group ($p = 0.0141$, $p = 0.0150$ and $p = 0.0312$, respectively). In all three situations, the average POCUS CO was less than the average invasive CO. These three groups had ICC values that were interpreted as being in almost perfect agreement. These results suggest that there is reliability and strong resemblance within each level, despite the statistically significant difference between the two cardiac outputs within each level. The ICC is large for most of the other levels in Table 3. Most of the levels have almost perfect or substantial agreement.

Comparing CO measurement using POCUS to either PA catheter or the PCA individually showed no significant difference, as shown in Table 3 and Fig. 3a, b. It is easy to see in the scatter plot figures that the points lie very close to the identity line, indicating that the measurements are similar. The Bland–Altman plot indicates that for the most part, the measurements tend to agree.

Discussion

Advancements in critical care medicine have extended the use of POCUS exponentially in the hands of the experienced intensivist. Less invasive methods are being used more often at the bedside to assess the patient's hemodynamics and avoid inherited risks, complications and some limitations associated with the invasive methods [3, 12, 13]. A pre-requisite of any method of monitoring is its accuracy, reproducibility and ease of use [4, 5]. Given the initial data presented here, with appropriate patient selection, this technique offers great promise as an accurate, easily accessible and no-risk means of measuring CO in the critically ill population.

Our study examined the use of POCUS of the common carotid artery to measure the CO and compare it to invasive modalities. The results showed almost perfect correlation between the Doppler flow volume measurement and the CO measured by other invasive techniques. Our patients were diverse, with different diagnosis for admission to the ICU.

Common carotid artery Doppler measurement is achievable in most patients, except those with neck injuries and cervical spine immobilization collars. In our study, we chose to examine the common carotid artery at the level of the thyroid gland and closer to its origin, rather than the proximal, middle and distal part near the bifurcation and carotid bulb as done in standard vascular carotid examination. Flow velocities near the bifurcation are different and turbulent flow which can affect the total results can be encountered. Our goal was different from the vascular examination done on the carotid artery for the purpose of evaluating stenosis and flow in internal, external carotid

Table 3 Wilcoxon signed-rank tests and intra-class correlation coefficients between the invasive and the ultrasound cardiac output measurements in different variables

Variable	Level	N	CO type	Mean $\pm$ SD (Min, Max)	p value	ICC	Agreement
Overall	–	36	Invasive	7.09 $\pm$ 1.84 (3.60, 12.30)	0.2629	0.8152	Almost perfect
			Ultrasound	6.86 $\pm$ 2.11 (3.15, 15.10)			
Carotid artery	Left	27	Invasive	6.77 $\pm$ 1.73 (3.60, 12.30)	0.0929	0.8705	Almost perfect
			Ultrasound	6.68 $\pm$ 2.34 (3.15, 15.1)			
	Right	9	Invasive	8.02 $\pm$ 1.92 (6.10, 11.40)	0.6523	0.4925	Moderate
			Ultrasound	7.37 $\pm$ 1.10 (5.75, 9.26)			
Gender	Male	17	Invasive	7.91 $\pm$ 2.14 (5.10, 12.30)	0.5791	0.7370	Substantial
			Ultrasound	7.69 $\pm$ 2.57 (3.92, 15.1)			
	Female	19	Invasive	6.35 $\pm$ 1.12 (3.60, 8.30)	0.0141	0.9316	Almost perfect
			Ultrasound	6.12 $\pm$ 1.24 (3.15, 8.25)			
Age group	<50	6	Invasive	8.54 $\pm$ 2.54 (5.79, 12.30)	0.3125	0.7696	Substantial
			Ultrasound	7.96 $\pm$ 3.72 (4.28, 15.10)			
	50–59	5	Invasive	7.18 $\pm$ 1.06 (6.06, 8.70)	0.4375	0.7532	Substantial
			Ultrasound	7.74 $\pm$ 1.85 (6.25, 10.21)			
	60–69	18	Invasive	7.03 $\pm$ 1.65 (5.00, 11.40)	0.1187	0.7807	Substantial
			Ultrasound	6.71 $\pm$ 1.50 (3.92, 9.65)			
	70–80	7	Invasive	5.90 $\pm$ 1.44 (3.60, 7.90)	0.0156	0.9914	Almost perfect
			Ultrasound	5.64 $\pm$ 1.42 (3.15, 7.39)			
PCA or PA catheter	PCA	24	Invasive	7.12 $\pm$ 2.03 (3.60, 12.30)	0.0312	0.8423	Almost perfect
			Ultrasound	6.77 $\pm$ 2.23 (3.15, 15.10)			
	PA catheter	12	Invasive	7.01 $\pm$ 1.45 (5.10, 10.50)	0.7334	0.7410	Substantial
			Ultrasound	7.03 $\pm$ 1.91 (3.92, 10.21)			
Mechanical ventilation	No	24	Invasive	6.87 $\pm$ 1.80 (3.60, 12.30)	0.1573	0.8896	Almost perfect
			Ultrasound	6.78 $\pm$ 2.44 (3.15, 15.1)			
	Yes	12	Invasive	7.52 $\pm$ 1.91 (5.65, 11.40)	0.2334	0.5515	Moderate
			Ultrasound	7.02 $\pm$ 1.27 (5.16, 9.26)			

The *p*-value was calculated using a paired *t* test

CO cardiac output, ICC intra-class correlation coefficient, PCA pulse contour analysis, PA pulmonary artery

and vertebral arteries. This location, the middle common carotid at the level of the thyroid gland, was found to correlate better with the CO during initial investigative and pilot examinations. Patient position with the head at 30° was chosen, since most critically ill patients are in this position and we did not want to change position and wanted to standardize the procedure and measurements.

Few studies have looked at estimating CO non-invasively by measuring the common carotid artery volume flow. Sinha et al. [11] studied the Doppler ultrasound flow volume in the common carotid artery in newborn infants and compared the flow to the left ventricular output using echocardiography. Infants with cerebral insults were excluded from the study. The position of the area sampled was away from the bifurcation as we did in our study. In their study, Sinha et al. found a strong correlation between the flow volume in the common carotid artery and the CO, and about 11 % of the CO was distributed to each common carotid artery. Other studies have also shown correlation

between the carotid artery Doppler flow volume measurement and the CO [15, 16].

Certain studies did not show the same results. Bernhard et al. [14] found a lack of correlation between the CO measured by echocardiography and the common carotid artery flow volume and cerebral perfusion obtained from the carotid artery Doppler. Their study like ours had a small sample size of 43 patients, and the modality of CO measurement was based on the echocardiographic measurements only and did not involve invasive techniques. Common carotid artery flow was measured by their neurology department technicians, and the location where the Doppler flow was sampled was not standardized only to the middle common carotid artery as we did in our study. CO measurements with the carotid Doppler in our study correlated very closely with the CO measured by the PA catheter and PCA. In our opinion, choosing the level of measurement of the volume flow at the level of the thyroid gland and not near the base and the bulb or bifurcation

allowed us to avoid flow turbulence and change in velocity in the internal and external carotid arteries, which can affect the total measurement. Our study also used different modalities other than echocardiography, such as the PA catheter which is considered the gold standard in many

instances, to measure the CO. This may have shown a better correlation between the common carotid flow volume measurement and the CO.

We generalized the flow volume in the common carotid artery to be 10 % of the total CO when comparing the

Fig. 2 **a** Scatter plot diagram showing the overall correlation between cardiac output measurements using invasive modalities versus ultrasound. **b** The Bland–Altman plot indicating that for the most part, the overall cardiac output measurements tend to agree with a mean difference close to zero and there is no statistical difference between the cardiac output measurement by invasive modality and ultrasound. $P = 0.262$. CO cardiac output in L/min

Fig. 3 **a** Scatter plot diagram showing the correlation between cardiac output measurements using the pulse contour analysis vs. ultrasound. CO cardiac output. PCA pulse contour analysis. **b** Scatter plot diagram showing the correlation between cardiac output measurements using the pulmonary artery catheter vs. ultrasound. CO cardiac output. PAC pulmonary artery catheter

Table 4 Wilcoxon–Mann–Whitney test for measuring the mean difference in cardiac output measurements with different variables

Variable	Level	N	Mean difference $\pm$ SD (Min, Max)	p value
Carotid artery	Left	27	0.09 ± 1.05 (–2.80, 1.51)	>0.999
	Right	9	0.64 ± 1.58 (–0.57, 3.82)	
Gender	Male	17	0.22 ± 1.72 (–2.80, 3.82)	>0.999
	Female	19	0.23 ± 0.44 (–0.64, 1.03)	
Age group (Years)	<50	6	0.56 ± 2.16 (–2.80, 3.82)	0.2972
	50–59	5	$–0.56 \pm 1.06$ (–2.38, 0.24)	
	60–69	18	0.32 ± 1.04 (–2.08, 2.80)	
	70–80	7	0.26 ± 0.19 (0.01, 0.51)	
PCA or PA catheter	PCA	24	0.35 ± 1.20 (–2.80, 3.82)	0.8013
	PA Catheter	12	$–0.02 \pm 1.22$ (–2.38, 1.51)	
Mechanical ventilation	No	24	0.09 ± 1.01 (–2.80, 1.51)	0.6030
	Yes	12	0.50 ± 1.53 (–2.07, 3.82)	

The p value was calculated using a paired t test
PCA pulse contour analysis, PA pulmonary artery

ultrasound method to the invasive one in our patient population. Further studies may elucidate a slight difference between the left and right carotid flow volumes and or variance in different degrees of stress.

Some limitations of carotid ultrasound were noted in this study, such as body habitus, vascular pathology, overlying indwelling venous catheters or surgical incisions, which may have limited its use in all patients. It is unclear if vascular pathology will alter the reliability of bedside ultrasound evaluation of CO and further studies into this sub-population are needed. Patients with suspicion of increased ICP (due to stroke or TBI or others) were excluded from this study. Changing cerebral auto-regulation and its effect on the common carotid artery volume flow was shown not to affect the relation between the percentage of the CO traversing the common carotid artery in some studies [11]. In our study on an adult population with no apparent cerebral pathology, the question of the effect of auto-regulation in the presence of cerebral pathology was not answered and will need a larger trial inclusive of such patients to test this hypothesis. A future perspective of this study design should address perfusion data in individual patients with impaired cerebral auto-regulation. It should be noted that some of the measured differences in CO were large, which may represent clinically important differences and indicate that larger studies are needed to validate these results.

Conclusion

Common carotid artery POCUS offers a non-invasive method of measuring CO in the critically ill population. Using carotid Doppler flow volume can help determine CO in patients with no apparent change in cerebral circulation and may expand the use of POCUS in the ICU, while limiting the need for invasive monitoring for the purpose of CO estimation.

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Conflict of interest The authors have no conflicts of interest.

Ethical standards All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki

Declaration of 1975, as revised in 2000 (5). All patients provided written informed consent to enrollment in the study and to the inclusion in this article of information that could potentially lead to their identification. The study was conducted in accordance with all institutional and national guidelines for the care and use of laboratory animals.

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