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ORIGINAL RESEARCH

Imaging

The effect of continuous positive airway pressure on inferior vena cava collapsibility as measured by bedside ultrasound

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Abstract

Objectives: The purpose of this study was to determine the impact of progressively increasing continuous positive airway pressure (CPAP) on measurements of the caval index (CI) using bedside ultrasound at the 3 common inferior vena cava (IVC) evaluation sites.

Methods: This was a prospective, observational trial that included 165 healthy adults over 18 years old enrolled between February 2015 and May 2018. Measurements of the IVC were obtained during normal tidal respirations from the subxiphoid area in the long and short axis and from the right mid-axillary line in the long axis. Measurements were obtained in each of these locations at atmospheric pressure and with CPAP at 5, 10, and 15 cmH2O. The CI was then calculated for each of the 3 selected locations at each level of pressure.

Results: As CPAP pressures increased from 0 to 15 cmH2O the CI measurements obtained at the lateral mid-axillary line did not show any statistically significant variation. There was a statistically significant difference ($P < 0.001$) when comparing measurements of the CI from the lateral mid-axillary line location to both anterior locations. As CPAP pressures increased, the CI calculated from the subxiphoid area in both the anterior short and anterior long axis orientations initially trended upwards at 5 cmH2O, then began to downtrend as the pressures increased to 10 and 15 cmH2O. Comparing the CI measurements from the anterior long and anterior short axis at 0, 5, 10, and 15 cmH2O, there was no statistically significant difference at any pressure ($P > 0.05$).

Conclusion: When evaluating the IVC in a spontaneously breathing patient, measurements from an anterior orientation are preferred as the lateral mid-axillary view can underestimate CI calculations.

KEYWORDS

caval index, continuous positive airway pressure, inferior vena cava, point-of-care ultrasound

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1 INTRODUCTION

1.1 Background

Balancing intravascular volume status is essential for optimal cardiac function. New technologies have been used to evaluate fluid status, but these technological advancements are expensive, invasive, time intensive to set up, require patient intubation and sedation, and may be inaccurate in critically ill patients. Examples of such hemodynamic monitoring systems include bioreactance devices and evaluating thermodilution or pulse contour analysis with the use of both arterial and venous catheters. The use of these technologies may not be feasible in the critically ill spontaneously breathing patient.[1–4]

1.2 Importance

Quantitatively speaking, there have been a variety of measurements that have come and gone out of favor with multiple studies showing heavy heterogeneity in patient selection and techniques used, as well as different set thresholds to predict fluid responsiveness.[5,6] Parameters investigated include static measurements such as right atrial pressure and pulmonary artery occlusion pressure to dynamic measurements such as respiratory variations in pulse pressure and stroke volume. Given the conflicting data produced by many studies, it is difficult to support the use of one parameter over the other. In fact, 1 study showed that dynamic parameters are underused or misused, whereas static parameters have been virtually abandoned in critically ill patients.[7]

A dynamic ultrasound measurement with potential utility in spontaneously breathing patients is the inferior vena cava (IVC) diameter. Prior studies suggest that IVC collapsibility may reflect the potential hemodynamic response to volume expansion.[8–16] Muller et al. found that in spontaneously breathing patients, the collapsibility index of the IVC greater than 40% is considered to be fluid responsive.[13] Barbier et al. found that in septic ventilated patients 18% distensibility index had a 90% sensitivity and specificity for discriminating volume responsiveness.[17] Feissel et al. found that in intubated patients, a 12% IVC respiratory variation discriminated between fluid responsive and non-responsiveness with a 93% positive predictive value.[18]

Clinically, many patients may fall in the spontaneously breathing cohort that require temporary pressure support and do not need a definitive airway. We set out to investigate the IVC dynamics using the caval index (CI) in a patient who is awake and is undergoing the use of non-invasive positive pressure ventilation and to determine how these dynamics change with increasing pressure levels.

1.3 Goals of this investigation

The primary objective of this study was to determine the effect of continuous positive airway pressure on the CI.

The Bottom Line

Although ultrasound evaluation of the inferior vena is useful in guiding resuscitation, it is currently unknown how non-invasive positive pressure ventilation effects the variation in IVC collapsibility. In this study of 165 healthy volunteers, increasing continuous positive airway pressure reduced variations in inferior vena cava collapsibility. Anterior views were also better than the lateral.

2 MATERIALS AND METHODS

2.1 Study design, setting, and selection of participants

This was an institutional review board approved, prospective, observational trial from February 2015 to May 2018. We included 165 healthy adult participants over 18 years old with no contraindications to continuous positive airway pressure (CPAP). Study participants included medical students, residents, faculty, and administrative staff from the University of Texas Health San Antonio Emergency Department. All subjects provided written informed consent. This study was completed in the University of Texas Health San Antonio Center for Clinical Ultrasound Education (https://wp.uthscsa.edu/lsom-ultrasound/) using Sonosite M-Turbo (Fujifilm Sonosite Inc., Bothell, WA) ultrasound machines.

2.2 Study protocol

Transducer selection with either the curvilinear C60xi transducer or the phased-array P21x transducer was based on sonographer preference. During the respiratory cycle the IVC moves caudally and cranially with the diaphragm leading to intra- and intersubject variation in the selected anatomic sites of IVC measurement. The Sonosite M-Turbo does not allow for real-time B-Mode visualization during M-Mode analysis leading to uncertainty in the location and orientation of measurements during the respiratory cycle. Further, the fixed axis of the M-Mode line may not allow for appropriate orientation to the narrowest perpendicular axis of the IVC because of variable patient anatomy. For these reasons we determined B-Mode to be the preferable method of measurement to ensure consistency in perpendicular measurements at the selected anatomic locations.

For this study, we used the Respironics BiPAP Vision (Koninklijke Philips Inc., Amsterdam, Netherlands) non-invasive positive pressure (NIPPV) machine. The hardware connected to the NIPPV machine included a non-invasive circuit with a proximal pressure line and disposable exhalation port that was attached to an Iso-gard HEPA light filter. This circuit was then attached to a Philips Respironics single-use 4-point oro-nasal headgear with Leak 1 Entrainment Elbow that the subject wore. The NIPPV masks varied in size from small to medium to large. In order to select the appropriate mask size for the study participants, their face was measured with the given mask fitting system that accompanies the headgear.

Before any data collection each study participant was placed in the supine position for 5 minutes to allow time for the IVC to equilibrate. Once equilibrated, IVC measurements were obtained at ambient pressure with no CPAP (0 cmH2O) using the 3 orientations described. The CPAP mask was then applied with an initial pressure of 5 cmH2O and the participants were given 1–2 minutes to acclimate to the applied pressure in the supine position before IVC evaluation and measurements. This protocol was then repeated at pressures of 10 and 15 cmH2O. Depending on body habitus and subject comfort level, the total time required to collect data for each subject varied from 20 to 45 minutes.

2.3 | Measurements

Measurements of the IVC were obtained during normal respiration at the end of both inspiration and expiration. In order to ensure that measurements were obtained at the correct phases of respiration, the IVC was imaged in B-mode while observing the subject breathing. The IVC was observed during normal respiration noting collapsibility during inspiration and expansion during expiration. After appreciating the respiratory variation and optimizing the location of IVC evaluation, the image was frozen and still-frames were cine-looped to identify the narrowest and widest diameter that coincided with the subject's inspiratory and expiratory phase. IVC measurements were obtained under B-mode at 3 different orientations: (1) the subxiphoid long axis orientation 3 cm from the junction of the right atrium and IVC, (2) the subxiphoid short axis orientation near the hepatic vein bifurcation, and (3) the right mid-axillary line long axis orientation 3 cm from the junction of the right atrium and IVC.

Ultrasound measurements of the IVC were obtained by 2 emergency ultrasound fellowship-trained board-certified emergency faculty (C.S. and C.G.) as well as 4 emergency medicine residents ranging from postgraduate years 2–3 (J.F., N.S., A.S., J.S.). One of these residents participated in and completed an emergency ultrasound fellowship during the course of the research project (J.S.).

2.4 | Exposures

Study measurements were obtained in all 3 IVC locations at ambient pressure without CPAP (0 cmH2O) and with CPAP at pressures of 5, 10, and 15 cmH2O. CPAP was chosen over bilevel positive airway pressure in order to limit the number of external factors that may affect IVC collapsibility to a simple dichotomy of ambient pressure versus a certain level of constant pressure being present. The CI was calculated for each of the 3 selected locations at each level of pressure. Calculations for the CI were performed using the equation: (IVC end expiratory diameter − IVC end inspiratory diameter)/IVC end expiratory diameter and expressed as a decimal fraction.

2.5 | Analysis

We summarized the distributions using means, SD, medians, and interquartile ranges. The significance of variation in the CI with pressure and view was assessed with a mixed effects linear model with a random subject effect, 2 crossed within subject factors (view and pressure), and a compound symmetric autocorrelation matrix.[19] All statistical testing was 2 sided with a significance level of 5%. Corrections for multiple comparisons were not made. SAS Version 9.4 for Windows (SAS Institute, Cary, North Carolina) was used throughout.

3 | RESULTS

3.1 | Characteristics of study subjects

A total of 165 healthy study participants were involved in this project with a mean age of 27.3 (±6.7) years, ranging from 21 to 74 years of age, and a mean body mass index (BMI) of 24 (±3.7) ($P = 0.01$) with a range BMI of 18.1–39.1. The demographics by sex can be seen in Table 1.

3.2 | Main results

In healthy individuals breathing ambient pressure and while receiving CPAP at progressively increasing pressures, the lateral mid-axillary views did not demonstrate a CI consistent with both the anterior orientations. This is best visualized in Figure 1. In the lateral mid-axillary view, the mean CI values were at 0.141 at ambient room pressure, increased minimally to 0.157 with NIPPV at 5 cmH2O, then downtrended to 0.130 and 0.134 at 10 and 15 cmH2O, respectively. When comparing the lateral mid-axillary orientation to the anterior long and anterior short axis orientations, the measurements of the mean CI showed a statistically significant difference ($P < 0.001$).

The anterior long and short axis orientations of the IVC demonstrated similar mean CI measurements that were not statistically significant from each other at ambient pressure or at any CPAP study pressure level. Of note, the mean CI had the tendency to initially increase as pressure is initially raised from 0 to 5 cmH2O and then the mean CI decreased as pressures increased from 5 to 10 cmH2O and 10 to 15 cmH2O.

3.3 | Limitations

Limitations of our research project include no standardized control over respiratory parameters while the participant was undergoing CPAP. At the time of consent, there was no clarification to the subjects on how to breathe with the NIPPV mask; therefore, there may have been some significant variability in the type of inspiration (diaphragmatic vs thoracic), tidal volumes, and the amount of negative inspiratory force applied by the subject. Although we did attempt to

TABLE 1 Demographics by gender

Demographic		Female	Male	Total	*P* value
Age	N	76	89	165	
	Mean (SD)	28.1 (8.9)	26.6 (3.8)	27.3 (6.7)	0.14
	Median	25.5	26	26	
	Range	22, 74	21, 42	21, 74	
Body mass index	N	76	89	165	
	Mean (SD)	23.3 (4.1)	24.7 (3.2)	24 (3.7)	0.01
	Median	22	24.3	23.4	
	Range	18.1, 37.4	19.6, 39.1	18.1, 39.1	

Abbreviation: SD, standard deviation.

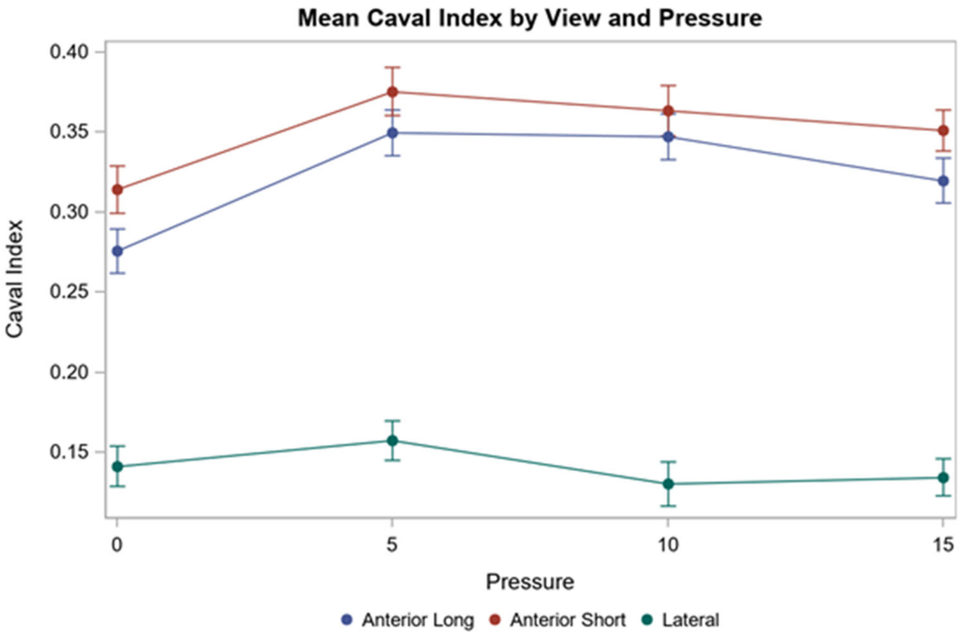

FIGURE 1 Mean caval index by view and pressure. Whiskers extend from the mean to the mean ± 1 SEM (standard error of mean).

keep mask leaks to a minimum with the use of oro-nasal masks, there was no documentation of measured mask leaks. There was a lack of heterogeneity in the population we evaluated as the majority of the subjects were all healthy young adults. There was also no evaluation of hydration status before data collection. The amount of time it took to collect data from each of the study participants varied between each data collector from 20 to 45 minutes. This could have been due to numerous factors including the sonographer's skill level and experience, the participant's body habitus, baseline IVC collapsibility, and poor views of the IVC secondary to bowel gas.

Additionally, there were data missing for subjects 26 and 107. For subject 26, it was difficult to obtain an anterior short-axis view at 0, 5, 10, and 15 cmH2O and an anterior long axis view at pressures 5, 10, and 15 cmH2O. Of note, subject 26's BMI was 25.06. For subject 107, it was difficult to obtain lateral mid-axillary measurements at 0, 5, 10, and 15 cmH2O. Of note, subject 107's BMI was 33.67. Measurements for subjects 26 and 107 were both obtained by J.S. Given the missing data from these subjects they were not included in the comparative analysis of different study orientations with regard to mean CI by pressures provided in Table 2.

4 | DISCUSSION

This study was designed to investigate the impact of increasing levels of CPAP on the CI parameter from 3 common evaluation sites of the IVC: subxiphoid long, subxiphoid short, and lateral mid-axillary orientations. From our results, the CI values obtained in the lateral mid-axillary view were lower than those obtained in both the anterior long and short-axis orientations ($P < 0.001$). In agreement with our study, Shah et al displayed the same correlation where the CI of the right mid-axillary coronal view was significantly lower than the CI of the subcostal sagittal view and also proved the IVC has the tendency to collapse in an anterior-posterior direction.[20]

TABLE 2 View contrasts[a,b] with regard to mean caval index by pressure (November 5, 2021)

		View						
Pressure		**Anterior long**	**Anterior short**	**Lateral**	**Contrast**	***P* value**	**Mean (SE)**	**95% CI**
0	N	165	164	164				
	Mean (SD)	0.276 (0.178)	0.314 (0.19)	0.141 (0.159)	Long vs short	0.021	−0.039 (0.017)	(−0.072, −0.006)
	Median	0.25	0.315	0.14	Long vs lateral	<0.001	0.135 (0.017)	(0.102, 0.168)
	Range	−0.32, 0.83	−0.37, 1	−0.29, 0.78	Short vs lateral	<0.001	0.174 (0.017)	(0.141, 0.207)
5	N	164	164	164				
	Mean (SD)	0.35 (0.183)	0.375 (0.193)	0.157 (0.156)	Long vs short	0.128	−0.026 (0.017)	(−0.059, 0.007)
	Median	0.35	0.37	0.135	Long vs lateral	<0.001	0.193 (0.017)	(0.16, 0.226)
	Range	−0.57, 1	−0.67, 1	−0.35, 0.64	Short vs lateral	<0.001	0.219 (0.017)	(0.186, 0.252)
10	N	164	164	164				
	Mean (SD)	0.347 (0.182)	0.363 (0.201)	0.13 (0.176)	Long vs short	0.339	−0.016 (0.017)	(−0.049, 0.017)
	Median	0.34	0.36	0.12	Long vs lateral	<0.001	0.218 (0.017)	(0.185, 0.251)
	Range	−0.33, 1	−0.93, 0.82	−1.07, 0.75	Short vs lateral	<0.001	0.234 (0.017)	(0.201, 0.267)
15	N	164	164	164				
	Mean (SD)	0.32 (0.179)	0.351 (0.163)	0.134 (0.148)	Long vs short	0.061	−0.032 (0.017)	(−0.065, 0.001)
	Median	0.325	0.35	0.1	Long vs lateral	<0.001	0.186 (0.017)	(0.153, 0.219)
	Range	−0.42, 0.79	−0.1, 0.81	−0.24, 0.71	Short vs lateral	<0.001	0.218 (0.017)	(0.185, 0.251)

[a] Adjusted for age, body mass index, and sex.

[b] Data from subject 26 and subject 107 were not used due to missing caval index values. Abbreviations: SE, standard error; SD, standard deviation; CI, caval index.

Another interesting finding from our study data was the CI measurements initially uptrended at 5 cmH2O, but then downtrended as we progressively increased pressures to 10 and 15 cmH2O indicating a decrease in IVC compliance with increased pressures. However, when considering the time required in adjusting the mask, acclimatizing to the CPAP pressures, and identifying and measuring the IVC at the different locations, up to 30 minutes had elapsed. Upon further research, it was noted that there can be decreased IVC compliance due to time rather than increased pressure. These findings can be attributed to the fluid shift that occurs from the extravascular to intravascular compartments when changing positions from standing to supine. This is consistent with the results of Folino et al where the first 30 minutes of their data collection was deemed a resting period where they allowed time to stabilize transcapillary fluid exchange. The trend they noted was decreased CI from the time at 0–30 minutes that was statistically significant.[21]

Before our data collection on each subject, there was no instruction on the type of breathing the subject should be performing, this was left to the subject's comfort level. Folino et al's and Kimura et al's studies also noted that the IVC diameter can be affected by different types of breathing manners, specifically diaphragmatic versus chest wall breathing.[21,22]

NIPPV such as CPAP can have multiple factors that can contribute and complicate the effects of the IVC dynamics including variable patient initiated tidal volumes, negative inspiratory force, current plasma volume of the patient, right heart function, intra-abdominal pressures, amount of positive end-expiratory pressure used, the type of breathing, and potential mask leaks.[15,23–24]

Future improvements on our work include studying a more heterogeneous cohort of participants; prolonging the equilibration time to 30 minutes before collecting data to reduce the potential impact of fluid shifting; expanding data collection to include parameters such as tidal volumes, mask leaks, hydration history, orthostatic vital signs, and abdominal circumference; and including subjects with underlying pathology. Given the results of our current research, we will only look into the anterior short and long-axis orientations to evaluate the IVC as the lateral mid-axillary orientation measurements appear to significantly underestimate IVC collapsibility.

In conclusion, our data suggest that CPAP may cause a decrease in IVC variability. However, there are confounders that may have contributed to this observation. Therefore, caution must be practiced when using CI as it is important not only to know the benefits of this hemodynamic monitoring method but also its limitations. Our data additionally show that when evaluating the IVC for collapsibility, it is best to do this from an anterior orientation, either anterior long or anterior short-axis views as lateral mid-axillary views can underestimate measurements.

AUTHOR CONTRIBUTION

All named authors have made substantial contributions to this paper including concepts and design, drafting and revising, and or final approval of the version submitted.

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