Ultrasound assessment of central venous pressure: A systematic review and meta-analysis

Jean Deschamps (jean3@ualberta.ca)
University of Alberta https://orcid.org/0000-0002-4872-3334

Jed Lipes
McGill University

Andrew Weinstock
McGill University

Dev Jayaraman
McGill University

Lawrence Rudski
McGill University

Jonathan Afilalo
McGill University Faculty of Science

Research

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Abstract

Background Ultrasound is increasingly relied upon to estimate central venous pressure (CVP) in the echocardiography lab and using point-of-care systems in the intensive care unit and the emergency department. However, there is uncertainty regarding the diagnostic accuracy of ultrasound-based parameters as reported in diverse studies.Methods A systematic review was performed by searching MEDLINE, EMBASE, and the Cochrane Database for studies evaluating ultrasound-based indicators of filling pressures in relation to catheterization-based CVP. Studies were screened for predefined inclusion criteria and rated for quality by duplicate observers. Standardized correlation coefficients for each ultrasound-based indicator were meta-analyzed using a random effects model.Results 3949 articles were screened and 64 met the criteria for inclusion. Inferior vena cava (IVC) diameter was assessed in 34 study measures and the pooled standardized correlation with invasive CVP was 0.74 (95% CI 0.63 to 0.84). IVC collapsibility was assessed in 20 study measures and the pooled standardized correlation with invasive CVP was -0.57 (95% CI -0.70 to -0.44). Tricuspid E/Ep was assessed in 6 study measures and the pooled standardized correlation with invasive CVP was 0.59 (95% CI 0.26 to 0.93). IVC parameters but not E/Ep remained correlated with CVP in mechanically ventilated patients, including cardiac surgery patients. Results were similar in studies featuring non-traditional users and cardiac specialists.Conclusions Echocardiographic IVC diameter, collapsibility, and tricuspid E/Ep ratio are significantly correlated with invasive CVP, albeit with important heterogeneity between studies. Most of these indicators are equally valid when applied in ventilated patients and by non-traditional users.

Introduction

Volume assessment is a fundamental component of the clinical exam in the office, ward, and critical care settings. Classical teaching has relied on the physical examination of the jugular venous pressure waveform (JVP), although its modest sensitivity of 33% and inter-observer reliability have increasingly led to the use of other tools (1–3). Invasive methods to assess the JVP, namely, the central venous pressure (CVP), require expertise in installation and interpretation, have inherent risks related to its invasiveness, and can be time consuming (1–3). Although controversial in its utility to predict volume responsiveness, the invasive determination of CVP remains the gold standard in measuring venous filling pressures (4,5).

Non-invasive determination of CVP was pioneered by echocardiographers and largely based on assessment of the inferior vena cava (IVC) using ultrasound systems in the echocardiography lab. Recently, point of care ultrasound systems have been developed and transformed the way physicians in critical care settings evaluate volume status. Newer techniques including 2-dimensional (2D) ultrasonography of the jugular and subclavian veins and Doppler interrogation of the right ventricle have been reported to be useful, although results have been inconsistent (particularly in mechanically ventilated patients) and day-to-day practice continues to rely on basic techniques of IVC size and collapsibility.

Thus, we performed a systematic review and meta-analysis of the ultrasound assessment of CVP to analyze which techniques provides the most accurate assessment of right atrial pressure in both mechanically ventilated and spontaneously breathing adult patients.

Methods

A systematic review was performed, searching Ovid MEDLINE(1946-), Ovid EMBASE(1974-), and the Cochrane Database using the search string: (Ultrasound OR Ultrasonography OR Echocardiogram OR Echocardiography OR Echocardiographic OR Doppler) AND ("Central venous pressure" OR "Right atrial pressure" OR "Jugular venous pressure" OR "Fluid status" OR "Volume status" OR "Filling pressure"). References from retrieved manuscripts were scanned for additional articles. English language studies using echocardiography and point of care ultrasound systems in the humans were included between 1980-2017.

Eligible articles were identified through two phases. In the first phase, two authors (JL, AW, or JD) independently reviewed the titles and abstracts of all retrieved bibliographic records for potential inclusion. In the second phase, full texts of the selected articles were retrieved and two authors independently reviewed and selected studies that met the inclusion criteria. Studies were included if right atrial pressure was estimated by ultrasound and directly compared to invasive CVP measured with a fluid filled catheter. Inclusion criteria included prospective and cross-sectional studies of adult (>=18 years of age) human patients, on spontaneous or mechanical ventilation, directly comparing absolute or dichotomized CVP using a fluid filled catheter to bedside 2D TTE or TEE of right atrial pressure, with or without Doppler. Exclusion criteria were studies focusing on congenital, retrospective studies, duplicate studies, and absence of comparison to the invasive CVP reference standard.

Patient characteristics, primary diagnosis, clinical setting, time between ultrasound and invasive measurement, and breathing status (mechanical ventilation or spontaneous breathing) were extracted from the original full text manuscripts. Echocardiographic parameters were recorded as continuous measures with their mean and standard deviation in the normal CVP and abnormal CVP groups, and as binary measures when dichotomized according to a given cut-point. For each parameter, correlation coefficients were extracted and transformed using Fisher's Z-transformation, and then meta-analyzed using a random effects model (STATA version 15). Meta-analyses were performed for all patients combined and subsequently for the spontaneously ventilated and mechanically ventilated subgroups. Heterogeneity was assessed with the I-squared statistic.

Quality of each study was independently analyzed by two authors (J.L, J.D or A.W) using the QUADAS-2 questionnaire for systematic reviews (6). Seven parameters (patient selection bias, patient selection applicability, index test (ultrasound) risk of bias, index test applicability, reference test (invasive CVP) risk of bias, and risk of bias due to timing were scored on a scale from 1 to 3; with 1 indicating low risk of bias, 2 indicating moderate risk, and 3 indicating high risk. Aggregate scores were averaged between the two reviewers. A score of 7-10 was defined as high quality, 11-14 as intermediate, and >14 as low.

Results

A total of 3949 articles were screened, 159 were identified for full-text review, and 64 met the prespecified selection criteria and were included in our analysis. The 29 studies (representing 34 measures) that reported on IVC size are shown in Table 1, the 19 studies (representing 20 measures) that reported on IVC collapsibility are shown in Table 2, and the 21 studies (representing 27 measures) that reported on right ventricular Doppler or tissue Doppler measures or peripheral vein measures are shown in Table 3 (these are not mutually exclusive as studies often reported on more than a single measure). In all studies, the reference standard was invasively measured CVP, generally performed within 0.5-1 hours from the time of the echocardiographic assessment. The quality of the studies assessed was high with the exception of 10 studies with intermediate ratings (13,33,34,45,49,56,57) and 3 studies with low ratings (20).

For IVC diameter as a continuous measure, 32 study measures were pooled and 2 study measures were not pooled because the R value was not available(15,63). The pooled standardized correlation with invasive CVP was 0.74 (95% CI 0.63 to 0.84) with significant heterogeneity across studies (I-squared 77.6%, P<0.01) (Figure 2). The correlation was similar in mechanically ventilated patients (0.79, 95% CI 0.61 to 0.97) than non-ventilated patients (0.70, 95% CI 0.57 to 0.83).

For IVC collapsibility as a continuous measure, 17 studies were pooled and 2 studies were not pooled because the R value was not available(15,63). The pooled standardized correlation with invasive CVP was -0.57 (95% CI -0.70 to -0.44) (Figure 3). The correlation was similar in mechanically ventilated patients (-0.56, 95% CI -0.77 to -0.34) than non-ventilated patients (-0.57, 95% CI -0.69 to -0.46), with significant heterogeneity in the former (I-squared 88.6%, P<0.01) but not the latter (I-squared 36.9%, P=0.135).

Among non-IVC parameters, only E/Ep was reported in at least 3 studies and thus was analyzed. This ratio represents the Doppler-measured trans-tricuspid inflow velocity divided by the tissue Doppler-measured lateral tricuspid annular velocity. For E/Ep as a continuous measure, 10 studies were included in the analysis. The pooled standardized correlation with invasive CVP was 0.62 (95% CI 0.24 to 0.99) with significant heterogeneity across studies (I-squared 92.7%, P<0.01) (Figure 4). The correlation was lower and not statistically significant in mechanically ventilated patients (0.39, 95% CI -0.57 to 1.34) whereas it was statistically significant in non-ventilated patients (0.71, 95% CI 0.25 to 1.17).

The subgroup of cardiac surgery patients was assessed in 8 studies (10,27,44,70) with a total of 547 patients. The 2 high quality studies (10,27) used the IVC diameter in mechanically ventilated patients and had correlation coefficients of 0.81 and 0.86 respectively. The subgroup of non-traditional users (NTU) was assessed in 15 studies, with the majority including both spontaneous and mechanically ventilated patients having a primary diagnosis of sepsis or respiratory failure. In these studies, the correlation coefficients were in keeping with the overall trends observed, ranging from 0.49 to 0.81 for IVC diameter, -0.32 to -0.40 for IVC collapsibility, and 0.62 to 0.84 for peripheral vein measures. Finally, Table 4 depicts the diagnostic performance of binary cut-points for echocardiographic parameters used in certain studies, wherein sensitivity ranged from 47-92% and specificity ranged from 72-100% for the various ultrasound parameters.

Discussion

Our meta-analysis encompassing a representative sample of patients and physician users has shown that ultrasound-based estimates of CVP are moderately correlated with invasive measures. In an undifferentiated population, the IVC diameter is the most highly correlated, followed by E/Ep, and lastly IVC collapsibility. The IVC diameter was similarly correlated in ventilated and non-ventilated patients, while the other parameters performed less well in ventilated patients. Given these findings, and the relative ease of measuring the IVC diameter, it is reasonable to utilize IVC diameter as the starting point to determine volume status if invasive monitoring is not warranted or available.

The findings of our meta-analysis demonstrate that the tricuspid E/Ep ratio is a promising parameter. E/Ep performed with moderate correlation in the non-ventilated group of patients. The performance of this test in mechanically ventilated group remains an unknown due the inclusion of only 2 studies in this subgroup of patients and requires further study. Possible reasons for low adoption of this parameter include the technical challenges inherent to performing this test, and the requirement of specialized ultrasound systems capable of performing Doppler and tissue Doppler measurements (which initial point of care ultrasound systems did not uniformly support). As the field of ultrasound continues to evolve from technological and pedagogical perspectives, a larger number of trained users will be equipped to implement the E/Ep and other advanced measures for the estimation of CVP.

Mechanically ventilated patients deserve special attention as they are a challenging subgroup of patients to study, and estimation of filling pressures is likely to be of great clinical relevance. In mechanically ventilated patients, the increased intrathoracic pressure exceeds intraabdominal pressures causing the IVC diameter to be larger than in spontaneously breathing patients. Despite this, the IVC diameter is still positively correlated with RAP (71). Moreover, insufflation during a passive mechanical ventilator-induced breath causes dilation rather than collapse of the IVC (71), rendering an opposite and less predictable correlation with RAP. In our study, the IVC diameter had the highest correlation and the narrowest CI of all the ultrasound measures evaluated, while IVC collapsibility had a reduced correlation with a wide CI, and the E/Ep had a non-significant correlation but included only 2 studies (44), Further study will be required before recommending IVC collapsibility or E/Ep in this group of patients.

Given the expanding interest and use of ultrasound by diverse practitioners, ultrasound-based assessment of CVP in no longer restricted to the cardiologist trained in echocardiography. Accordingly, the proportion of studies with non-traditional users was notable (30%). These studies generally focused on basic measures such as IVC diameter and reported correlation coefficients in line with those reported by traditional users. These data support the continued dissemination of echocardiographic training among non-traditional users in the intensive care unit, internal medicine, emergency medicine, and other fields.

Current guidelines from the ASE (72) are in line with the data currently covered in our systematic review and meta-analysis. Most of the studies included a dichotomization of CVP of > 10 mmHg corresponding with an IVC collapsibility > 40–50%. There was some discordance with IVC diameter, in that 3 out of 10 studies had significantly lower IVC diameter cut-off(17,25), but overall most studies had an IVC diameter corresponding to current recommendations.

First, the studies that were identified and reviewed evaluated the accuracy of ultrasound parameters in isolation and did not compare various combinations of parameters which may lead to greater diagnostic accuracy. Second, specific factors may interfere with the reliable use of IVC and right heart parameters as surrogates of CVP: these include tricuspid valve disease, etiology of right heart disease, pericardial disease, and atrial fibrillation. We could not determine presence or absence of these parameters from the published studies.

Finally, although it is important to understand how well ultrasound measures correlate to an invasive CVP, perhaps the more important question to be answered is how well ultrasound measures correlate to volume responsiveness.

Conclusions

Non-invasive ultrasound assessment of the IVC can be effectively performed at the bedside to estimate CVP and can be performed by cardiologists and non-traditional users across a broad spectrum of patients, including those on mechanical ventilation. Assessment of other parameters such as E/Ep may be complementary if confirmed in additional studies, provided that the expertise and equipment is in place to acquire them. The observed heterogeneity in the studies reviewed highlights the need for further high-quality studies with adequately powered sample sizes to be performed, comparing different parameters and testing the value of an integrated multi-parameter approach for estimating CVP.

Declarations

Ethics approval and consent to participate

This systematic review and meta-analysis did not acquire any primary patient data. All data was sourced from other studies. As such, ethics approval was not required to proceed with this study.

Consent for publication

All authors consent to publication of this manuscript.

Availability of data and materials

Competing interests

None declared.

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Authors' contributions

JD, JL and AW were responsible for the screening, selection and analysis of articles. JD, JL and JA were responsible for drafting the manuscript. All authors critically reviewed the manuscript. JL and JA were responsible for study design and conception. DJ and LR provided expert guidance for interpretation and generalizability of the results. JA was responsible for the statistical methods and analysis. All authors read and approved the final manuscript.

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Tables

Table 1: Characteristics of Studies Reporting IVC Size

Authors	Year	Setting	U/S modality	User	# Patients	Age	Primary diagnosis	Intubated	CS	Delay	R value	Quality Score	Quality Rating
Arthur ME	2009	ICU	TEE	Anesth	95	57	CS	Yes	Yes	0.5h	0.86	8.5	High
Avcil M	2016	ICU	POCUS	ICU	73	64	Sepsis	Mix	no	0h	0.29	7	High
Belfort MA	1994	ICU	TTE	Unclear	11	25	Sepsis	Mix	No	0.5h	0.87	10.5	Int
Bendjelid K	2002	ICU	TTE	NTU	20	62	Sepsis	Yes	No	0.5h	0.81	8.5	High
Bendjelid K	2002	ICU	TTE	NTU	20	62	Sepsis	Yes	No	0.5h	0.71	8.5	High
Blair JE	2009	Cardio	HHUS	Cardio	72	50	N/A	No	No	1h	N/A	8	High
Brennan JM	2007	Cardio	TTE	Cardio	91	50	CHF	No	No	1h	0.50	10	High
Brennan JM	2007	Cardio	TTE	Cardio	91	50	CHF	No	No	1h	0.60	10	High
Brennan JM	2007	Cardio	TTE	Cardio	91	50	CHF	No	No	1h	0.60	10	High
De Lorenzo RA	2012	ER/ICU	POC	NTU	65	67	RF	Mix	No	0.5h	0.51	19	Low
De Lorenzo RA	2012	ER/ICU	POC	NTU	65	67	RF	Mix	No	0.5h	0.49	19	Low
De Lorenzo RA	2012	ER/ICU	POC	NTU	65	67	RF	Mix	No	0.5h	0.50	19	Low
Jue J	1992	ICU	TTE	Cardio	49	58	RF	Yes	Yes	0.5h	0.58	9	High
Karacabey S	2016	ER	POCUS	ER	83	73	Sepsis	Yes	No	N/A	0.53	10	High
Kawata T	2017	Cardio	TTE	Cardio	120	54	CHF	No	No	0h	0.47	8	High
Lee SL	2014	Cardio	TTE	Cardio	369	56	CHF	No	No	24h	N/A	12	Int
Lorsomradee S	2007	OR	TEE	Anesth	70	68	CS	Yes	Yes	N/A	0.81	8	High
Marcelino P	2006	ICU	TTE	Unclear	477	62	Sepsis	Mix	No	0.5h	N/A	7.5	High
Mintz GS	1981	Cardio	TTE	Cardio	50	N/A	CHF	N/A	N/A	N/A	0.72	12	Int
Moreno F	1984	Cardio	TTE	Cardio	65	46	CHF	No	No	24h	0.40	13	Int
Muhamad N	2015	ER	POCUS	ER	25	60	Sepsis	No	No	0h	0.74	8	High
Nagdev AD	2010	ER	POC	NTU	73	63	N/A	Mix	No	0.5h	0.78	9.5	High
Nagdev AD	2010	ER	POC	NTU	73	63	N/A	Mix	No	0.5h	0.66	9.5	High
Naghipour B	2016	Cardio	TEE	Cardio	39	62	N/A	No	No	0h	0.85	7	High
Nakao S	1987	Cardio	TTE	Cardio	53	56	CAD	No	No	24h	0.57	10	High
Ommen SR	2000	Cardio	TTE	Cardio	71	56	CHF	No	No	0.5h	N/A	9.5	High
Patel AR	2011	CCU	TTE	Cardio	40	53	CHF	No	No	0.5h	0.56	10	High
Prekker ME	2013	ICU	POC	NTU	65	59	Sepsis	No	No	0.5h	0.76	9.5	High
Schefold JC	2010	ICU	POC	NTU	30	60	Sepsis	Yes	No	0.5h	0.56	7.5	High
Simonson J	1988	Cardio	TTE	Cardio	27	N/A	CHF	No	No	N/A	0.35	13.5	Int
Tsutsui RS	2014	Cardio	TTE	Cardio	71	56	CHF	No	No	0h	0.40	10	High
Utsunomiya H	2009	Cardio	TTE	Cardio	50	46	PAH	No	No	24h	0.6	11.5	Int
Worapratya P	2014	ER	POCUS	ER	30	N/A	Sepsis	No	No	0h	0.551	7	High
Yildirimturk O	2011	Cardio	TTE	Cardio	39	59	MS	No	No	0.5h	0.51	12.5	Int

(1) midpoint (end-inspiration); (2) at subxiphoid level (end-inspiration); (3) at supra-iliac level (end-inspiration); (4) end-inspiration; (5) end-expiration
TTE: Transthoracic Echo; TEE: Trans-esophageal Echo; HHUS: Hand-Held Ultrasound; POC: POCUS; CUSP: Custom Ultrasound-Pressure system; CS: Cardiac Surgery; RF: Respiratory Failure;
MS: Mitral Stenosis; CHF: Congestive Heart Failure; CAD: Coronary Artery Disease; CV: Cardiovascular surgery; SAH: Subarachnoid Hemorrhage; PAH: Pulmonary Arterial Hypertension; S: Surgery
NTU: Non traditional user, defined as Non-Cardio trained. Cardio: Cardiologist, or cardiac sonographer; Anesth: Anesthesia

Table 2: Characteristics of Studies Reporting IVC Collapsibility

Authors	Year	Setting	U/S modality	User	# Patients	Age	Primary diagnosis	Intubated	CS	Delay	R value	Quality Score	Quality Rating
Prekker ME	2013	ICU	POC	NTU	65	59	Sepsis	No	No	0.5h	-0.40	9.5	High
Patel AR	2011	CCU	TTE	Cardio	40	53	CHF	No	No	0.5h	-0.49	10	High
Yildirimturk O	2011	Cardio	TTE	Cardio	39	59	MS	No	No	0.5h	0.56	12.5	Int
Nagdev AD	2010	ER	POC	NTU	73	63	N/A	Mix	No	0.5h	.-0.67	9.5	High
Utsunomiya H	2009	Cardio	TTE	Cardio	50	46	PAH	No	No	24h	-0.60	11.5	Int
Stawicki SP	2009	ICU	POC	NTU	101	58	Surgical	Mix	No	0.5h	-0.32	8	High
Blair JE	2009	Cardio	HHUS	Cardio	71	50	N/A	No	No	1h	N/A	8	High
Brennan JM	2007	Cardio	TTE	Cardio	91	50	CHF	No	No	1h	-0.50	10	High
Brennan JM	2007	Cardio	TTE	Cardio	91	50	CHF	No	No	1h	-0.50	10	High
Marcelino P	2006	ICU	TTE	unclear	477	62	Sepsis	Mix	No	0.5h	N/A	7.5	High
Nagueh SF	1996	ICU	TTE	Cardio	35	60	SAH	Mix	Yes	0.5h	-0.63	8	High
Jue J	1992	ICU	TTE	Cardio	49	58	RF	Yes	Yes	0.5h	0.13	9	High
Nakao S	1987	Cardio	TTE	Cardio	53	56	CAD	No	No	24h	-0.48	10	High
MoreNo F	1984	Cardio	TTE	Cardio	65	46	CHF	No	No	25h	0.71	13	Int
Karacabey S	2016	ER	POCUS	ER	83	73	sepsis	All	no	N/A	-0.72	10	High
Kawata T	2017	Cardio	TTE	cardio	120	54	CHF	No	No	0h	-0.40	8	High
Lee SL	2014	Cardio	TTE	Cardio	369	56	CHF	No	No	24h	N/A	12	Int
Sobczyk D	2015	ICU	POCUS	ICU	50	64	CS	All	Yes	0h	-0.19	9	High
Stawicki SP	2014	ICU	POCUS	ICU	79	56	S	Mix	No	0h	0.42	9	High
Worapratya P	2014	ER	POCUS	ER	30	N/A	Sepsis	No	No	0h	-0.72	7	High

(1) midpoint (end-inspiration); (2) at subxiphoid level (end-inspiration); (3) at supra-iliac level (end-inspiration); (4) end-inspiration; (5) end-expiration
TTE: Transthoracic Echo; TEE: Trans-esophageal Echo; HHUS: Hand-Held Ultrasound; POC: POCUS; CUSP: Custom Ultrasound-Pressure system; CS: Cardiac Surgery; RF: Respiratory Failure;
MS: Mitral Stenosis; CHF: Congestive Heart Failure; CAD: Coronary Artery Disease; CV: Cardiovascular surgery; SAH: Subarachnoid Hemorrhage; PAH: Pulmonary Arterial Hypertension; S: Surgery
NTU: Non traditional user, defined as Non-Cardio trained. Cardio: Cardiologist, or cardiac sonographer; Anesth: Anesthesia

Table 3: Characteristics of Studies Reporting Non-IVC Parameters

CVP Comparator	Authors	Year	Setting	U/S modality	User	# Patients	Age	Primary diagnosis	Intubated	CS	Delay	R value	Quality Score	Quality Rating
TV E/E'	Tsutsui RS	2014	Cardio	TTE	Cardio	71	56	CHF	No	No	0h	0.19	10	High
TV E/E'	Said K	2012	CCU	TTE	Cardio	50	50	ACS	No	No	0.5h	0.84	13.5	Int
TV E/E'	Patel AR	2011	CCU	TTE	Cardio	N/A	53	CHF	No	No	0.5h	0.09	10	High
TV E/E'	Sade LE	2007	ICU	TTE	Cardio	101	60	CS	Mix	Yes	N/A	0.70	8.5	High
TV E/E'	Sade LE	2007	ICU	TTE	Cardio	53	63	ICU	Mix	No	N/A	0.83	8.5	High
TV E/E'	Sade LE	2007	ICU	TTE	Cardio	36	56	CS	Mix	Yes	N/A	0.41	8.5	High
TV E/Ea	Michaux I	2006	OR	TEE	Anesth	44	63	CS	Yes	Yes	0.5h	-0.11	9.5	High
TV E/Ea	Nagueh MF	1999	Cardio	TTE	Cardio	62	68	CAD	Mix	No	0.5h	0.75	9.5	High
TV E/Ea	Sundereswaran L	1998	Cardio	TTE	Cardio	38	53	HT	Yes	Yes	N/A	0.79	10.5	High
TV E/Ea	Arbo J	2013	ICU	POC	NTU	30	62	Sepsis	Mix	No	0.5h	N/A	8.5	High
TV E/A ratio	Patel AR	2011	CCU	TTE	Cardio	17	53	CHF	No	No	0.5h	0.57	10	High
TV E/A ratio	Utsunomiya H	2009	Cardio	TTE	Cardio	50	46	PAH	No	No	24h	0.80	11.5	Int
TV E/A ratio	Nagueh SF	1996	ICU	TTE	Cardio	35	60	SAH	Mix	Yes	0.5h	0.66	8	High
Peripheral Vein	Thalhammer C	2009	ICU	POC	NTU	50	67	CS	Mix	Yes	N/A	0.62	8.5	High
Peripheral Vein	Thalhammer C	2007	ICU	CUSP	NTU	50	69	Sepsis	Mix	No	N/A	0.84	8	High
Peripheral Vein	Baumann UA	2005	ICU	POC	NTU	32	60	CS	Mix	unclear	0.5h	N/A	8	High
IJ height	Avcil M	2016	ICU	POC	ICU	73	64	Sepsis	Mix	No	0h	0.66	7	High
IJ height	Muhamad N	2015	ER	POCUS	ER	25	60	Sepsis	No	No	0h	0.64	8	High
IJ size	Avcil M	2016	ICU	POCUS	ICU	73	64	Sepsis	Mix	No	0h	0.54	7	High
IJ size	Hossein-Nejad H	2016	ER	POCUS	ER	52	58	Sepsis	No	No	0h	0.44	9	High
IJ area	Avcil M	2016	ICU	POCUS	ICU	73	64	Sepsis	Mix	No	0h	0.50	7	High
IJ area	Hossein-Nejad H	2016	ER	POCUS	ER	52	58	Sepsis	No	No	0h	0.63	9	High
IJ area/CCA ratio	Hossein-Nejad H	2016	ER	POCUS	ER	52	58	Sepsis	No	No	0h	0.74	9	High
IJ ratio 30/0 degree	Hilbert T	2016	ICU	POCUS	Anesth	47	68	CS	Yes	Yes	0h	N/A	9	High
SVC collapsibility	Cowie BS	2015	ICU	TEE	Anesth	91	69	CS	All	Yes	0h	-0.21	9	High
SVC size	Cowie BS	2015	ICU	TEE	Anesth	91	69	CS	All	Yes	0h	0.04	9	High
Femoral vein diameter	Cho RJ	2016	ICU	POCUS	ICU	97	59	N/A	All	No	N/A	0.66	11	Int

(1) midpoint (end-inspiration); (2) at subxiphoid level (end-inspiration); (3) at supra-iliac level (end-inspiration); (4) end-inspiration; (5) end-expiration
TTE: Transthoracic Echo; TEE: Trans-esophageal Echo; HHUS: Hand-Held Ultrasound; POC: POCUS; CUSP: Custom Ultrasound-Pressure system; CS: Cardiac Surgery; RF: Respiratory Failure;
MS: Mitral Stenosis; CHF: Congestive Heart Failure; CAD: Coronary Artery Disease; CV: Cardiovascular surgery; SAH: Subarachnoid Hemorrhage; PAH: Pulmonary Arterial Hypertension; S: Surgery
NTU: Non traditional user, defined as Non-Cardio trained. Cardio: Cardiologist, or cardiac sonographer; Anesth: Anesthesia

Table 4: Characteristics of Studies Reporting Binary IVC Parameters

CVP Comparator	Authors	U/S Modality	User	# Patients	Primary Diagnosis	Intubated	Cardiac surgery	Delay	Cutoff Dichotomization	C-statistic	Sensitivity	Specificity	Quality Score	Quality Rating
IVC collapsibility	Prekker ME	POCUS	NTU	65	Sepsis	No	No	0.5h	50%	0.66	47	77	9.5	High
IVC collapsibility	Patel AR	TTE	Cardio	40	CHF	No	No	0.5h	40%	0.67	77		10	High
IVC collapsibility	Nagdev AD	POCUS	NTU	73	NA	Mix	No	0.5h	50%	0.93	91	91	9.5	High
IVC collapsibility	Blair JE	HHUS	Cardio	71	NA	No	No	1h	45%		91	72	8	High
IVC collapsibility	Brennan JM	TTE	Cardio	91	CHF	No	No	1h	20%	0.93	73	82	10	High
IVC collapsibility	Brennan JM	TTE	Cardio	91	CHF	No	No	1h	40%	0.91	73	84	10	High
IVC collapsibility	Nagueh SF	TTE	Cardio	35	SAH	Mix	Yes	0.5h	50%		72	76	8	High
IVC collapsibility	Kawata T	TTE	Cardio	120	CHF	No	No	0h	40%	0.78	75	81	8	High
IVC collapsibility	Lee SL	TTE	Cardio	369	CHF	No	No	24h	30%	0.84	75	83	12	Int
IVC size	Lee SL	TTE	Cardio	369	CHF	No	No	24h	1.9 cm	0.82	75	78	12	High
IVC size	Kawata T	TTE	Cardio	120	CHF	No	No	0h	1.7 cm	0.9	92	76	8	High
IVC size	Avcil M	ICU	POCUS	73	Sepsis	Mix	No	0h	1.9 cm	0.62	43	90	7	High
IVC size	Prekker ME	POCUS	NTU	65	Sepsis	No	No	0.5h	2.0 cm	0.91	85	81	9.5	High
IVC size	Utsunomiya H	TTE	Cardio	50	PAH	No	No	24h	2.35 cm	0.85	87	83	11.5	Int
IVC size	Blair JE	HHUS	Cardio	72	NA	No	No	1h	2.0 cm		82	84	8	High
IVC size	Brennan JM	TTE	Cardio	91	CHF	No	No	1h	2.0 cm	0.76	73	85	10	High
IVC size	Brennan JM	TTE	Cardio	91	CHF	No	No	1h	1.5 cm	0.88	91	79	10	High
IVC size	Brennan JM	TTE	Cardio	91	CHF	No	No	1h	1.2 cm	0.92	91	94	10	High
IVC size	Jue J	TTE	Cardio	49	RF	Yes	Yes	0.5h	1.2 cm		25	100	9	High
TV E/E'	Said K	TTE	Cardio	50	ACS	No	No	0.5h	4.5	0.95	89	100	13.5	Int
TV E/E'	Sade LE	TTE	Cardio	53	ICU	Mix	No	N/A	4	0.93	88	85	8.5	High
TV E/E'	Sade LE	TTE	Cardio	36	CS	Mix	Yes	N/A	4	0.56	44	73	8.5	High
TV E/A ratio	Utsunomiya H	TTE	Cardio	50	PAH	No	No	24h	7.3	0.92	87	97	11.5	Int
TV E/Ea	Nagueh MF	TTE	Cardio	62	CAD	Mix	No	0.5h	1.1		66	92	9.5	High

(1) midpoint (end-inspiration); (2) at subxiphoid level (end-inspiration); (3) at supra-iliac level (end-inspiration); (4) end-inspiration; (5) end-expiration
TTE: Transthoracic Echo; TEE: Trans-esophageal Echo; HHUS: Hand-Held Ultrasound; POC: POCUS; CUSP: Custom Ultrasound-Pressure system; CS: Cardiac Surgery; RF: Respiratory Failure;
MS: Mitral Stenosis; CHF: Congestive Heart Failure; CAD: Coronary Artery Disease; CV: Cardiovascular surgery; SAH: Subarachnoid Hemorrhage; PAH: Pulmonary Arterial Hypertension; S: Surgery
NTU: Non traditional user, defined as Non-Cardio trained. Cardio: Cardiologist, or cardiac sonographer; Anesth: Anesthesia
All studies listed used definition of >10 mm Hg for elevated RAP, except Nagueh SF, Nagdev AD, who used 8 mm Hg.

Figures

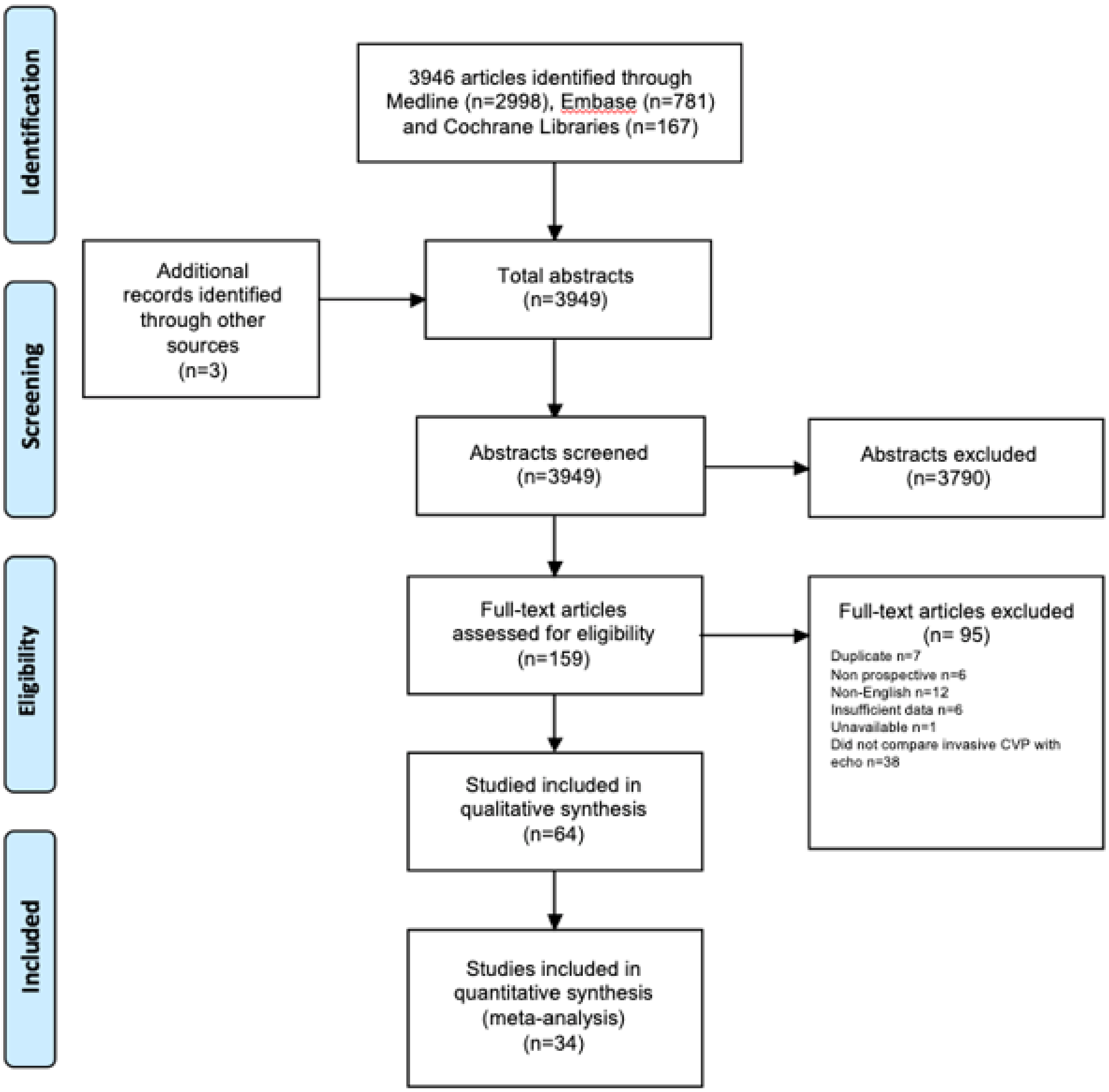

Figure 1

Flow Diagram

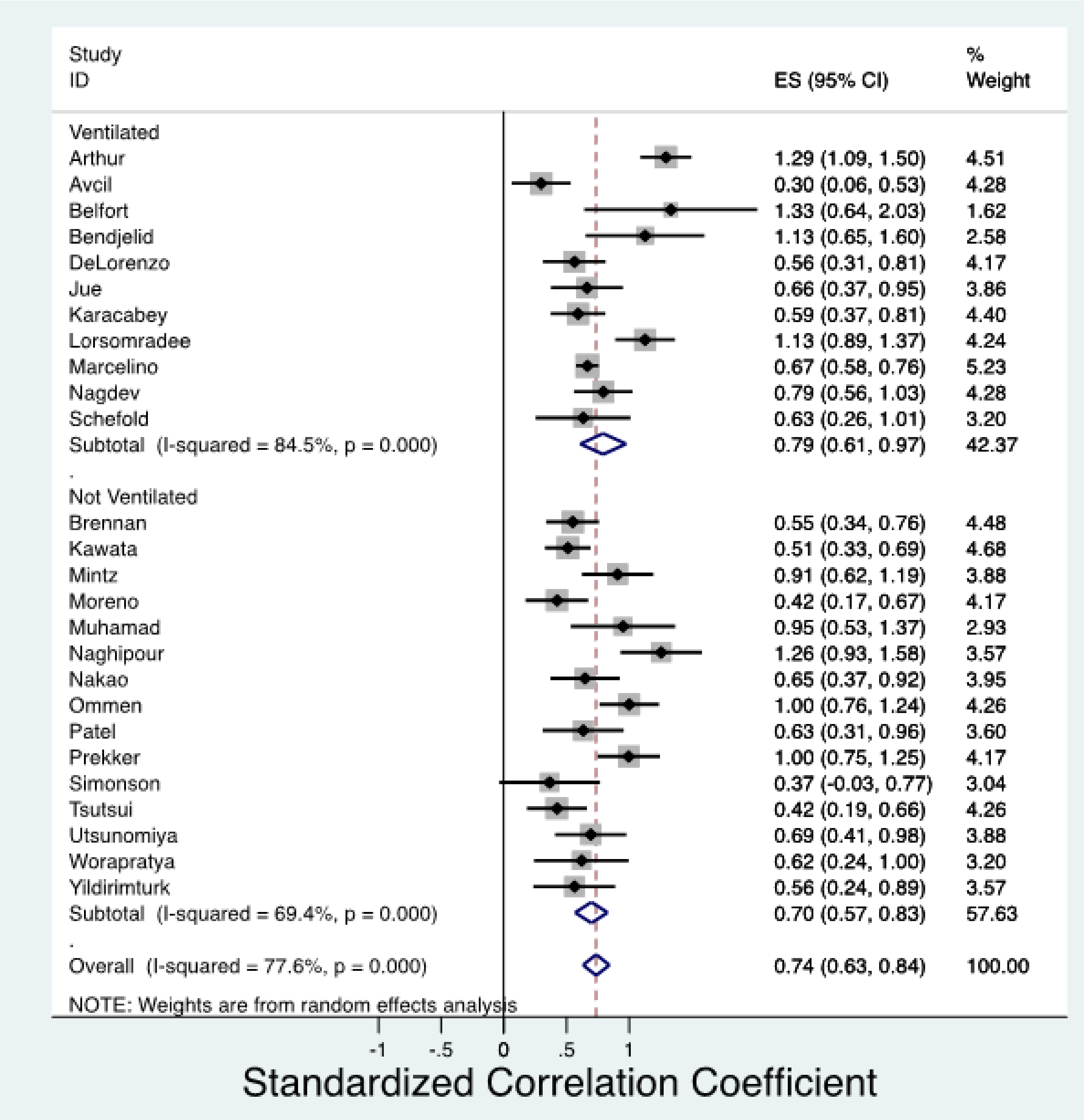

Figure 2

Forest Plot for Echocardiographic IVC Diameter and Invasive CVP

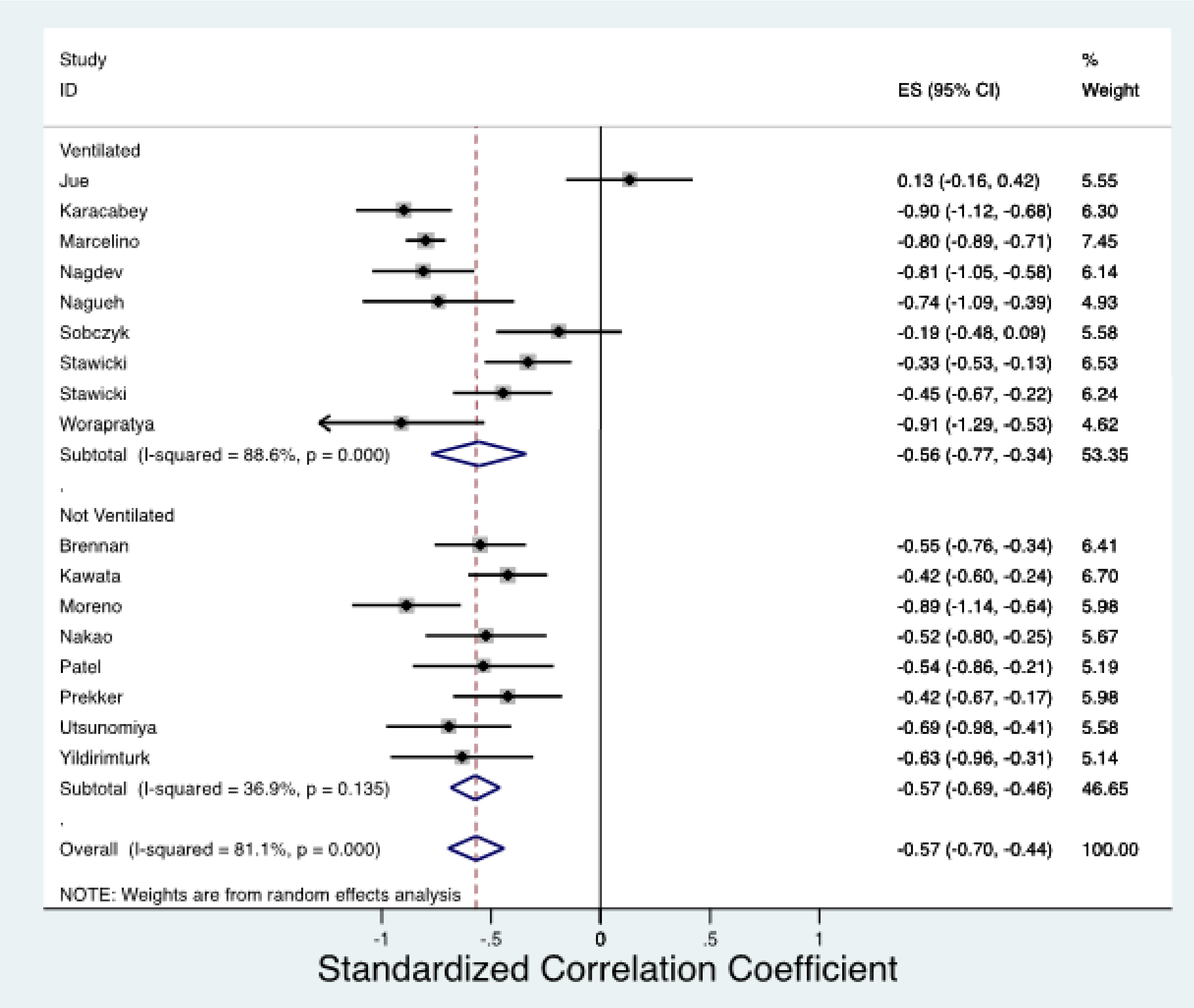

Figure 3

Forest Plot for Echocardiographic IVC Collapsibility and Invasive CVP

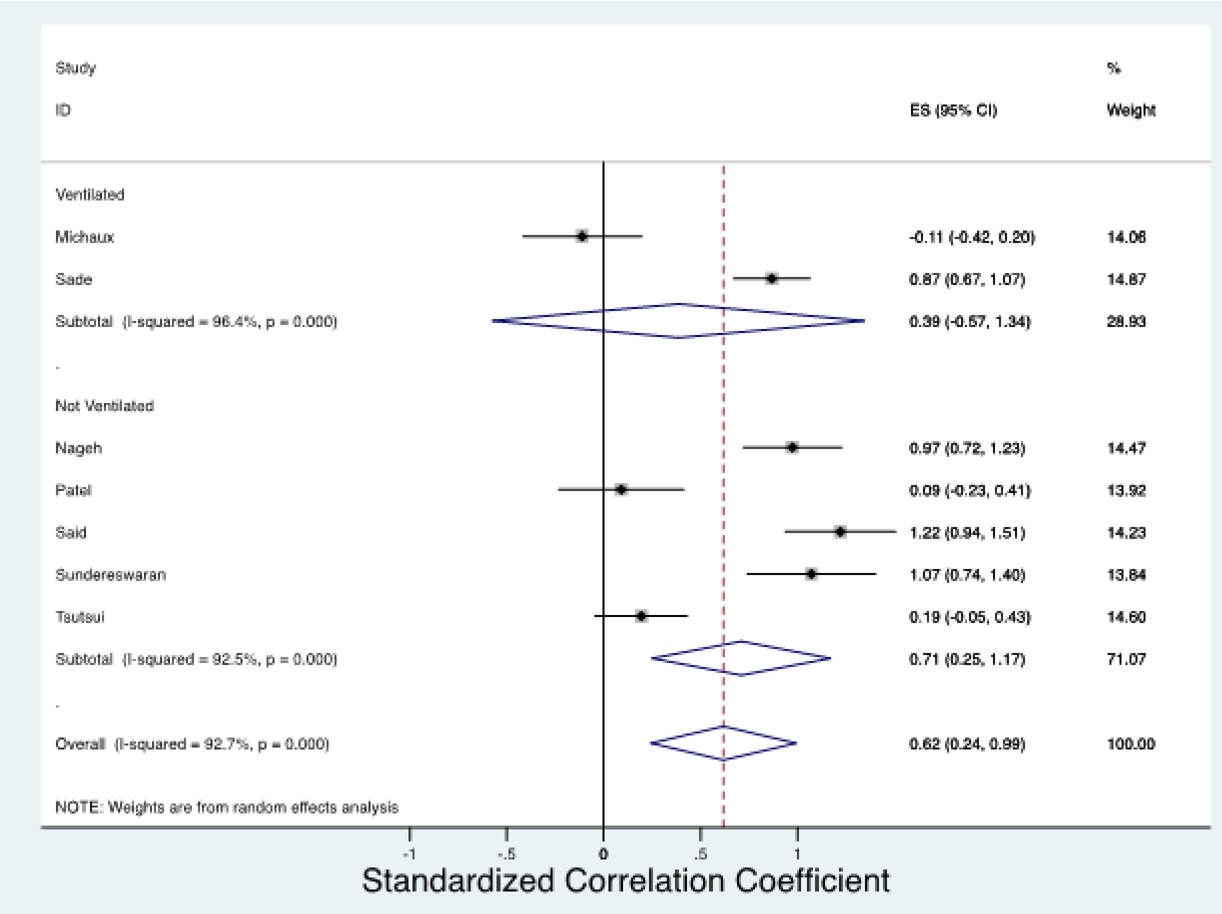

Figure 4

Forest Plot for Echocardiographic E/Ep Ratio and Invasive CVP