Approach to Echocardiography in ARDS Patients in the Prone Position: A Systematic Review

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Abstract

Echocardiography is commonly utilized in patients with acute respiratory distress syndrome (ARDS) for assessment of cardiac function, volume status, and the potential development of acute cor pulmonale. In severe ARDS, prone positioning is frequently used, which imposes technical challenges during transthoracic echocardiography (TTE) image acquisition. Moreover, prone positioning can affect cardiopulmonary function in ways that are reflected on the echocardiographic findings in this position. Historically, a transesophageal approach was recommended when a patient is prone, with few studies reporting utility of TTE in this setting. However, recent publications have begun to address this knowledge gap. This review explores recent literature addressing the use of TTE in prone patients with ARDS, with a special focus on the cardiopulmonary effects of proning and potential solutions to the technical difficulties that arise in this position.

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Running Title:

Echocardiography in The Prone Position.

Abstract:

Echocardiography is commonly utilized in patients with acute respiratory distress syndrome (ARDS) for assessment of cardiac function, volume status, and the potential development of acute cor pulmonale. In severe ARDS, prone positioning is frequently used, which imposes technical challenges during transthoracic echocardiography (TTE) image acquisition. Moreover, prone positioning can affect cardiopulmonary function in ways that are reflected on the echocardiographic findings in this position. Historically, a transesophageal approach was recommended when a patient is prone, with few studies reporting utility of TTE in this setting. However, recent publications have begun to address this knowledge gap. This review explores recent literature addressing the use of TTE in prone patients with ARDS, with a special focus on the cardiopulmonary effects of proning and potential solutions to the technical difficulties that arise in this position.

Keywords:

Echocardiography in the prone position, Cardiopulmonary changes in prone positioning, Utility of Echocardiography in ARDS patients, Optimizing transthoracic echocardiographic views in the prone position.

Background:

ARDS is a life-threatening inflammatory lung disorder that presents as acute hypoxic respiratory failure along with bilateral airspace involvement, developing within 7 days of an insult. According to the degree of hypoxemia, it is classified as mild, moderate and severe ARDS. Severe ARDS is diagnosed when the ratio of partial pressure of arterial oxygen (PaO2) relative to the fraction of inspired oxygen (FiO2) (P/F ratio) is less than 100 mmHg . Early initiation of prone positioning within the first 36 hours of mechanical ventilation is one strategy that has been shown to improve oxygenation, reduce the extent of mechanical ventilator-induced lung injury and reduce 90-day mortality in patients with severe ARDS . Many respiratory and cardiovascular changes occur when patients are placed in the prone position. Detecting and monitoring these changes by echocardiography can play an important role in assessing the impact of the lung injury on the pulmonary circulation and right ventricle, including monitoring the development or progression of acute cor pulmonale; which is estimated to affect 20-25% of this patient population. Moreover, echocardiography is a clinically useful tool that is readily available for the assessment of hemodynamic instability that may arise in patients with severe ARDS . However, prone positioning imposes certain challenges limiting acoustic windows in these patients . While transesophageal route was previously the recommended approach to obtaining echocardiography in ARDS patients in the prone position , the COVID-19 pandemic resulted in unprecedented increased demand on the acute care resources and resulted in increased numbers of severe ARDS cases requiring prone positioning. Transesophageal echocardiography (TEE) may not be feasible and readily available given the current constraints in many hospitals . Therefore, transthoracic echocardiography (TTE) is increasingly being utilized in proned patients given its feasibility and wide availability in the majority of medical institutions . The aim of this review is to discuss the current literature on the hemodynamic changes that may arise in proned ARDS patients and highlight its impact on the echocardiographic findings in this position. Moreover, we will explore the utility of echocardiography in ARDS patients in the prone position and describe the technical challenges that are encountered while obtaining TTE in this clinical context and seek their potential solutions.

Literature Search:

PubMed, Google Scholar, Cochrane library and Medline were used to search for original articles, systematic review articles, narrative review articles, case series studies, case reports and editorial communications, using the following pre-selected keywords and search terms: Echocardiography in prone positioning, Transthoracic echocardiography in prone positioning, Transesophageal echocardiography in prone positioning, physiological changes associated with prone positioning in ARDS patients, cardiac changes in proned ARDS patients, right ventricular changes in ARDS, right ventricular changes in prone positioning, left ventricular changes in ARDS, left ventricular changes in proned ARDS patients, echocardiographic assessment of the left ventricle in prone position, echocardiographic assessment of the right ventricle in prone position, echocardiographic assessment of valvular abnormalities in prone position, utility of echocardiography in ARDS patients, early echocardiographic signs of acute cor pulmonale, disadvantages and limitations of echocardiography in ARDS patients.

Articles published in English from January 1, 1970 through December 15th, 2020 were eligible for inclusion (Figure 1). Exclusion criteria included studies of healthy individuals, pediatric populations, and studies focused on renal or cerebrovascular blood flow.

Effects of prone positioning on the cardiopulmonary function:

In non-intubated and spontaneously breathing individuals, the diaphragmatic movements favor ventilation of the dorso-caudal regions of the lungs, while at the same time, gravity and the pulmonary vascular geometry drive the majority of the blood distribution to the same regions, reducing the ventilation-perfusion (V/Q) mismatch . In contrast, when a sedated and passively mechanically ventilated patient is in the supine position, tidal volumes are preferentially delivered to the ventral lung regions due to increased anterior versus posterior chest wall compliance . Moreover, the dorsal lung zones are exposed to the compressive effect of the edematous ventral lung tissues and overlying heart in the supine position, resulting in over-perfusion of the poorly ventilated dorsal lung zones and under-perfusion of the ventral zones resulting in increased dead space. Prone positioning unloads the dorsal lung zones from the compressive effect of the overlying heart and consolidated lung, and displaces the diaphragm in the caudal axis, providing improved aeration of the posterior lung zones . Clinically, this is often reflected by an improvement in oxygenation and possibly reduction in the positive end expiratory pressure (PEEP) requirements when transitioning a patient from supine to prone .

Prone positioning similarly affects the pulmonary circulation and the right ventricle (RV) by reducing the external mechanical compression of the vascular beds in the dorsal lung, which increases the transmural pulmonary vascular pressures in those same regions, resulting in increased vascular dimensions and reduced PVR. Moreover, improved aeration of the dorsal lung regions in the prone position may reduce hypoxic vasoconstriction in this region. These changes have the net effect of reducing RV afterload . Decreased anterior chest wall compliance during proning also increases the intra-thoracic pressure during delivery of the tidal volumes in volume-controlled ventilator modes , which may increase the intra-pleural pressure relative to alveolar pressure and result in reduced transpulmonary pressure (Alveolar pressure – Intrapleural pressure) . Reduced transpulmonary pressure may lower the RV afterload, which is directly related to the transpulmonary gradient . Interestingly, higher alveolar pressures, and hence transpulmonary pressures, are particularly pronounced in ARDS that results from a direct pulmonary insult such as COVID-19 pneumonia, as compared to extra-pulmonary causes of ARDS. Thus, the protective effects of prone positioning on the RV may be more pronounced in these cases . Changes in RV function and afterload are readily detected on echocardiography in the prone position by measuring the reduction in RV end diastolic volume index , left ventricle (LV) systolic eccentricity index, incidence of tricuspid regurgitation and septal dyskinesia .

In contrast to the RV, effects of proning on the systemic circulation, venous return and LV function are variable. Prone positioning increases the intra-abdominal pressure, which can augment venous return from the intra-abdominal vascular beds . However, in patients with preexisting intra-vascular volume depletion, this increased intra-abdominal pressure may alternatively impede venous return by compressing the inferior vena cava (IVC) . Therefore, effects of prone positioning are highly dependent on patient's volume status. Similarly, proning may increase the LV stroke volume and cardiac index only in patients with preload reserve, possibly due to increased venous return from the pulmonary vascular beds to the LV, reduced RV afterload and increased right cardiac output (Figure 2).

Utility of Echocardiography in severe ARDS:

Echocardiography in the setting of ARDS can provide valuable information regarding the impact of lung injury on the pulmonary circulation and RV function , and prognostic information related to the development of acute cor pulmonale, which affects 20%-25% of the patients with ARDS, increasing in incidence with lung injury progression . Detecting or monitoring the progression of RV dilatation on echocardiography may predict the development and/or worsening of acute cor pulmonale , although this measurement lacks sensitivity. Nonetheless, evidence of RV dilation can prompt considerations for acute pulmonary embolism as well as changes to hemodynamic management .

Other echocardiographic parameters that can be used as early markers of the development of acute cor pulmonale include the tricuspid early diastolic velocity, measured from the myocardial tissue doppler profiles

. Reduction of the tricuspid early diastolic velocity might be present prior to excessive RV functional compromise. Moreover, in the early phase of acute cor pulmonale, septal dyskinesia at the end of systole might appear, reflecting right ventricular systolic overload . If the inciting factor (hypoxia, hypercapnia, low PH or impaired lung compliance) persists or worsens, it can progress to right ventricular diastolic overload as well, manifesting as paradoxical septal motion and septal displacement/flattening throughout both diastole and systole. On the other hand, estimating the systolic pulmonary arterial pressure or right ventricular systolic pressure (RVSP) by measuring the maximal velocity of the tricuspid backflow can help predict the extent of V/Q mismatch. However, the RVSP must be cautiously interpreted because it also depends on the right ventricular stroke output, which is reduced in acute cor pulmonale . Further assessment of the RV function can be obtained from the tricuspid annular plane systolic excursion (TAPSE) and S' of the tricuspid annulus. These parameters were adequately obtained via the four-chamber view in the majority of patients in the prone position.

Generally speaking, encountering findings suggestive of acute core pulmonale should prompt efforts to optimize ventilator setting that reduce RV stress. Although the ideal ventilator approach has not been tested in a randomized controlled trial to date, ventilator settings should be adjusted to limit the plateau and driving pressures in order to reduce lung stress, reverse hypoxia induced pulmonary vasoconstriction and avoid hypercapnia . Prone positioning can be considered in this scenario to help facilitate right ventricular protective ventilation . Additionally, interventions should include optimization of volume status using diuretics when appropriate, use of inotropic agents to support myocardial contractility and treatment with inhaled pulmonary vasodilators in select patients. Mechanical circulatory support devices, such as veno-venous extracorporeal membrane oxygenation (VV-ECMO), may also be appropriate in refractory cases . Repeated daily echocardiographic assessment of the RV function in these situations is advised to follow the progression and/or resolution of such dreaded complication .

The LV has its share of the cardiac manifestations in ARDS. It may be affected by the inciting disease process itself, such as septic cardiomyopathy or COVID-19 induced myocarditis , or its function can be affected by the consequences of ARDS-induced changes on the pulmonary circulation and RV function. In light of the decreasing use of pulmonary arterial catheters in the medical intensive care units , echocardiography plays a crucial role in assessing the left ventricular function and detecting the presence of discordant filling between the left and right ventricles, known as ventricular interdependence . Fluid administration in these patients should be done with careful attention to biventricular function. Volume expansion in the setting of an elevated pulmonary vascular resistance as in ARDS patients may result in RV-end diastolic enlargement. Once the point of maximal compliance of the pericardial sac is reached, any further RV dilation may occur at the expense of LV-end diastolic compliance, resulting in reduced LV stroke volume and pump failure eventually . Detailed echocardiographic assessment of the inter-ventricular septal motion, bi-ventricular dimensions and detecting impaired left ventricular filling by mitral flow profiles, can help avoid volume overload in these tenuous patients .

Feasibility of Transthoracic Echocardiography in the Prone Position:

Since the beginning of COVID 19 pandemic in December 2019, there has been increasing interest in echocardiography in ARDS patients in the prone position (Table 1). Prior to that, only few studies investigated this area . Transesophageal echocardiography has historically been recommended for obtaining echocardiographic examination in the prone position based on the assumption that TTE would lack adequate acoustic windows in the prone position. Increased air artifact from high PEEP and increased lung artifact from pulmonary edema may also complicate views in this position. However, the COVID 19 pandemic has overwhelmed the medical infrastructure and placed extraordinary demands on available medical resources, contributing in part to the expansion of TTE use .

	Number of patients	**Average BMI**	**Average PEEP in the prone position**	**Pr**
Gibson et. Al 2020	27	31 +/- 5 kg/m2	13 +/- 3 cm H2O	TT
Garcia-Cruz et. al 2020	15	28.98 kg/m2	Not reported	TT

Giustiniano et. al 2020	8	Not reported	15 +/- 2.6 cmH2O	TT
Marvaki et. al 2020	21	28 +/- 4.6 kg/m2	Not reported	TE
Jaglan et. al 2020	1	Not reported	Not reported	TT
Rali et. al 2020	1	50 kg/m2	20 cmH2O	TT

Table 1. Summary of previous studies investigating TTE in ARDS patients in the prone position. (BMI: Body Mass Index. PEEP: Positive End Expiratory Pressure. TTE: Transthoracic Echocardiography. ARDS: Acute Respiratory Distress Syndrome. BMI: Body Mass Index. PEEP: Positive End Expiratory Pressure. IVC: Inferior Vena Cava).

Optimizing the Transthoracic windows:

Although prone positioning presents many technical difficulties when obtaining a TTE exam, reduced anterior lung distension and an anterior shift in the heart's position within the thorax may actually improve windows in some patients . When performing a prone exam, positioning the patient in a "swimmer" position (Figure 3) has been suggested in literature ; where the patient's left arm is extended above the head. A pillow can be placed underneath the left shoulder to elevate the lateral chest from the surface of the bed. The transducer is then placed at the point of maximal impulse in the left flank close to the midclavicular line at the level of the 4^{th} or 5^{th}intercostal space with the indicator pointing posteriorly. From this location, an apical 4-chamber view is readily available. A 5-chamber view can also be obtained by tilting the probe towards the patient's abdomen. Adequate assessment of the RV parameters including chamber size and dimensions, TAPSE and tricuspid annular velocity are obtainable from the apical window in this position. It is also possible to assess the tricuspid regurgitation peak gradient, as a marker of the systolic pulmonary arterial pressures, in addition to the LV functional parameters such as the chamber size, mitral annular plane systolic excursion (MAPSE) and mitral inflow signals. Increased BMI (>30 kg/m^2) and PEEP levels (>10 mmHg) did not preclude obtaining satisfactory images in the majority of studied patients . An alternative strategy implements deflating a section of the air mattress underlying the lower thoracic area to create more space for the transducer, without the need to place the patient's left arm above the shoulder.

Assessment of the IVC:

Echocardiographic measurement of the IVC distensibility is a noninvasive hemodynamic monitoring tool that can help guide fluid resuscitation in supine mechanically ventilated ARDS patients . The same measurement can be utilized in the prone position to guide fluid therapy . To obtain a transthoracic image of the IVC in the prone position, the transducer can be placed horizontally in the right flank with the indicator pointing towards the patient's head (Figure 4). Once the IVC is visualized, the 4-chamber subcostal view can also be obtained through tilting the transducer towards the left shoulder and then rotating it clockwise .

Assessment of the RV, LV and pulmonary circulation:

Use of echocardiography early after initiation of proning allows assessments of changes involving both ventricles and pulmonary circulation in ARDS patients (Figures 5). Improvement of the RV global longitudinal strain , pulmonary vascular resistance, reduction of RV afterload and reversal of septal dyskinesia are all expected changes following prone positioning. Despite the advents and proposed innovations in obtaining a TTE exam in the prone position, certain parameters such as the LV eccentricity index and end systolic septal dyskinesia can only be assessed via the parasternal short axis view, which can be a difficult to obtain using the TTE probe in the prone position . An interesting technique described by Maravaki et. al , where the TEE probe was used to obtain transthoracic images in the prone position, may help overcome this limitation. In this technique, the patients were left in the classic prone position while the TEE probe is slid between the patient and mattress obliquely from the left shoulder towards the mid-sternum, leaving the probe tip in the parasternal position at the level of the 3^{rd} or 4^{th} intercostal space. Long axis parasternal views can be obtained in this position. Moreover, by manipulating the probe angle to 60-120 degrees, the short axis parasternal view may be obtained at the mitral valve level. An apical short axis view can also be visualized by rotating the probe clockwise. This technique yielded satisfactory images in 81% of test cases .

TEE in the prone position:

Standard use of TEE in the prone position is not without potential limitations and pitfalls. for example, lateral head rotation during pronation imposes certain technical difficulties on inserting the TEE probe and manipulation . Introducing the TEE probe under direct laryngoscope guidance can be an option. Inserting the probe while the patient is still in the supine position right before turning to the prone position is another option . If difficulties are still encountered inserting the probe, use of a pediatric probe may be considered. The decision to choose TEE vs TTE in prone ARDS patients should be individualized based on the echocardiographic exam indication and physician familiarity with procedural options. Although TTE can provide evaluation of multiple cardiac parameters in the prone position, TEE can allow for more windows to be evaluated and provide equal image quality in both supine and prone positions (Table 2). Moreover, TEE can be used to detect a broader spectrum of the hemodynamic changes associated with prone positioning, some of which might not be achievable via TTE exams given the limitations on obtaining the parasternal short axis view in the prone position .

TTE in the prone position
Pros: -Less labor intensive -Lower incidence of complications and side effects -Available in the majority of institutions at th
Cons: -Limited to the apical and lateral IVC windows -Difficulty obtaining Tricuspid regurgitation peak gradient in obese a

Table 2 . TTE vs TEE in ARDS patients in the prone position. (TTE: Transthoracic Echocardiography. TEE: Transesophageal Echocardiography. ARDS: Acute Respiratory Distress Syndrome. PEEP: Positive End Expiratory Pressure. IVC: Inferior Vena Cava).

Future Research:

The full spectrum of the physiological and echocardiographic changes that arise with prone positioning have not been completely explored yet. Although the current literature has revealed significant improvements of the pulmonary vascular resistance and right ventricular function associated with pronation , changes involving other cardiovascular parameters such as the left ventricular function and ventricular synchrony have not been fully analyzed. Studies comparing echocardiographic images in both supine and prone position did not detect statistically significant changes in these elements. Nonetheless, the majority of these studies involved a relatively small number of patients and require further validation in a larger population to ensure broader generalizability of their results . Moreover, why some patients benefit from prone positioning and others do not is not entirely understood. Reports on patients who deteriorated following proning indicated that the LV and RV functions worsened immediately . The cause for ventricular decompensation is uncertain, but highlights the potential role of echocardiography in detecting early signs of cardio-pulmonary functional limitations or trends following pronation to help identify patients at risk for clinical worsening following proning. The question whether to terminate pronation based on these findings and the utility of echocardiography in predicting hemodynamic and respiratory benefits from pronation is yet to be explored. Moreover, the decision to initiate proning to improve the pulmonary vascular resistance and RV function in patients with echocardiographic findings of acute cor pulmonale, yet with a P/F ratio of above 150 mmHg is another area of uncertainty that remains open to further investigations.

Conclusion:

Echocardiography offers an easy, rapid, and point-of-care assessment for detecting changes in cardiac function following prone positioning in ARDS patients. Multiple innovations have been proposed during the COVID-19 pandemic to improve transthoracic echocardiographic windows in the prone position and the decision for TTE versus TEE must weigh potential TEE risks against the value of the additional information gained over TTE. While larger studies are needed to further understand the spectrum of cardiopulmonary changes in proned patients, echocardiography's role continues to expand and remains an important tool in the care of ARDS patients.

List of Abbreviations:

ARDS: Acute Respiratory Distress Syndrome

TTE: Transthoracic Echocardiography

TEE: Transesophageal Echocardiography

PaO2: Arterial Oxygen Partial Pressure

FiO2: Fraction of inspired Oxygen

V/Q Ratio: Ventilation-Perfusion ratio

PEEP: Positive End Expiratory Pressure

RV: Right Ventricle

PVR: Pulmonary Vascular Resistance

LV: Left Ventricle

IVC: Inferior Vena Cava

CO: Cardiac Output

RVSP: Right Ventricular Systolic Pressure

TAPSE: Tricuspid Annular Plane Systolic Excursion

MAPSE: Mitral Annular Plane Systolic Excursion

VV-ECMO: Veno-Venous Extra-Corporeal Oxygenation

BMI: Body Mass Index

Author contributions:

MA searched the literature and constructed the main text. MD critically reviewed the article, provided comprehensive edits and contributed to the overall paper design. RR reviewed and edited the physiological as well as echocardiographic aspects of the paper and designed the illustrative figures. SM, AM & HR reviewed the article with a focus on the echocardiographic details and contributed to the overall article's design and figures selection.

References:

Figure Legends:

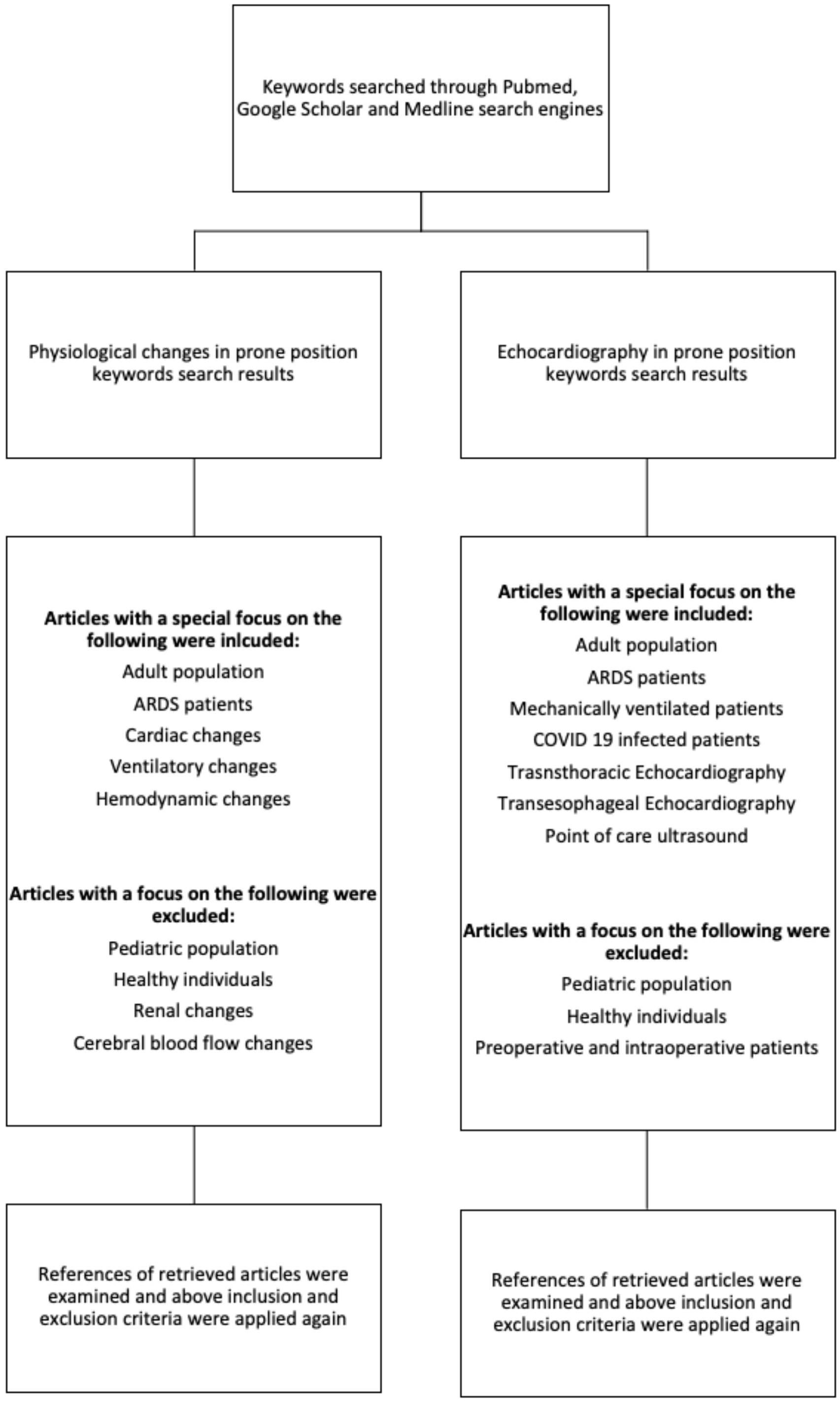
Figure 1. Flow chart illustrating the literature search methods used to retrieve the relevant articles, and the inclusion and exclusion criteria that were applied.

Figure 2. An illustration summarizing the cardiopulmonary changes that may arise when patients are placed in the prone position. PVR: Pulmonary Vascular Resistance. RV: Right Ventricle. LV: Left Ventricle. CO: Cardiac Output.

Figure 3. An illustration of the swimmer position where the left arm is extended above the head while a pillow is placed underneath the left shoulder to elevate the lateral chest from the surface of the bed. The transducer is placed close to the midclavicular line at the level of the 4^{th} or 5^{th} intercostal space with the indicator pointing posteriorly.

Figure 4. An illustration of transthoracic echocardiographic assessment of the IVC in the prone position. The transducer is placed in the right flank horizontally with the indicator pointing towards the patient's head. (IVC: Inferior Vena Cava).

Figure 5. Transthoracic echocardiographic assessment of right and left ventricular function in the prone position. (A): Apical four-chamber view. (B): Right & left ventricular dimensions ratio. (C): Tricuspid peak systolic S wave tissue Doppler velocity. (D): Tricuspid annular plane systolic excursion. (E): Left ventricular outflow tract velocity integral time. (F): Mitral annular plane systolic excursion. (G): E velocity of mitral inflow filling. (H): Lateral e' velocity. Reprinted from *Transthoracic echocardiography during prone position ventilation: Lessons from the COVID-19 pandemic* by E. Garcia-Cruz et al., 2020, *J Am Coll Emerg Physicians Open* , 1(5), 730-736. Labels could not be added. Copyright 2020 by The Authors. JACEP Open published by Wiley Periodicals LLC on behalf of the American College of Emergency Physicians. Reprinted with permission.


Keywords searched through Pubmed, Google Scholar and Medline search engines
Physiological changes in prone position keywords search results
Echocardiography in prone position keywords search results
Articles with a special focus on the following were inlcuded:
Adult population
ARDS patients
Cardiac changes
Ventilatory changes
Hemodynamic changes
Articles with a focus on the following were excluded:
Pediatric population
Healthy individuals
Renal changes
Cerebral blood flow changes
Articles with a special focus on the following were included:
Adult population
ARDS patients
Mechanically ventilated patients
COVID 19 infected patients
Trasnsthoracic Echocardiography
Transesophageal Echocardiography
Point of care ultrasound
Articles with a focus on the following were excluded:
Pediatric population
Healthy individuals
Preoperative and intraoperative patients
References of retrieved articles were examined and above inclusion and exclusion criteria were applied again
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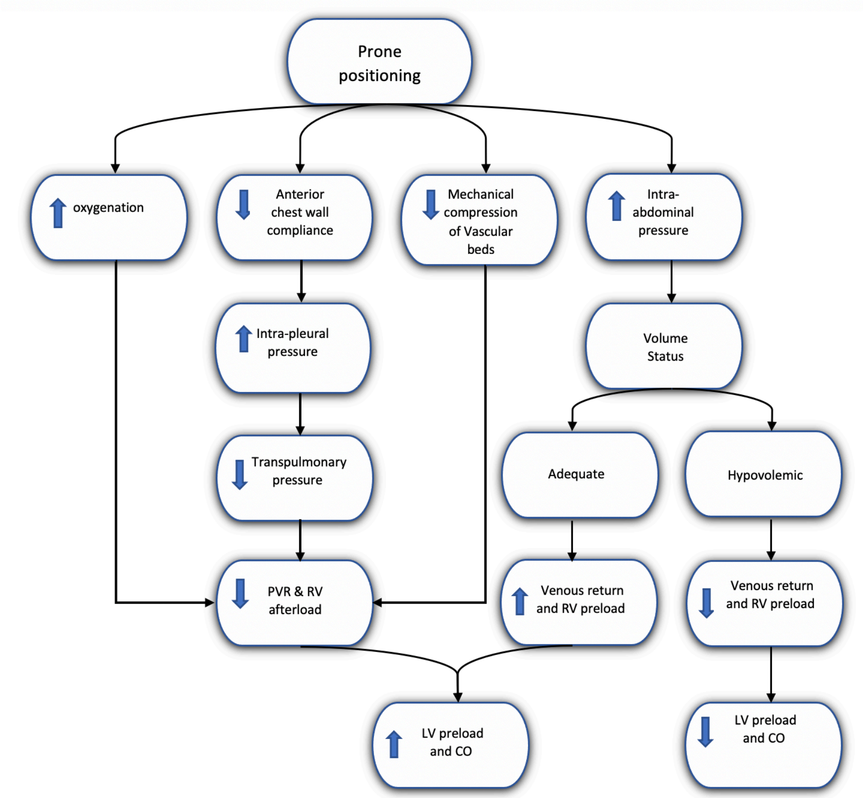
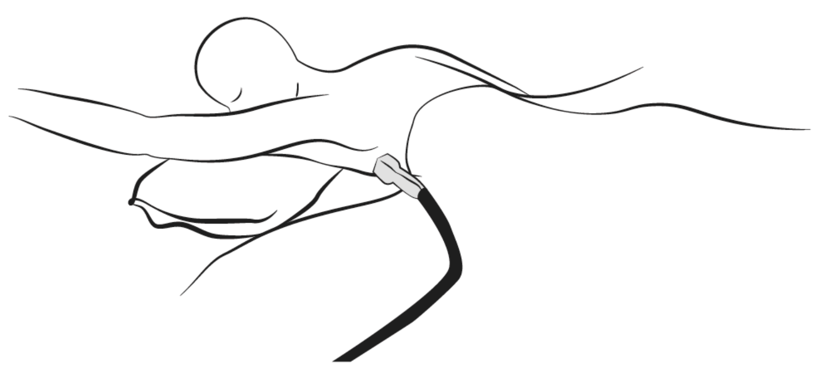
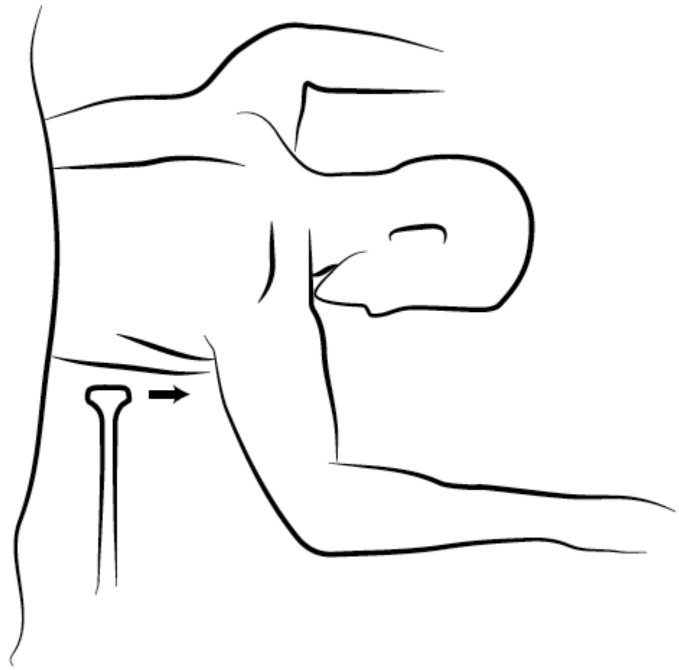
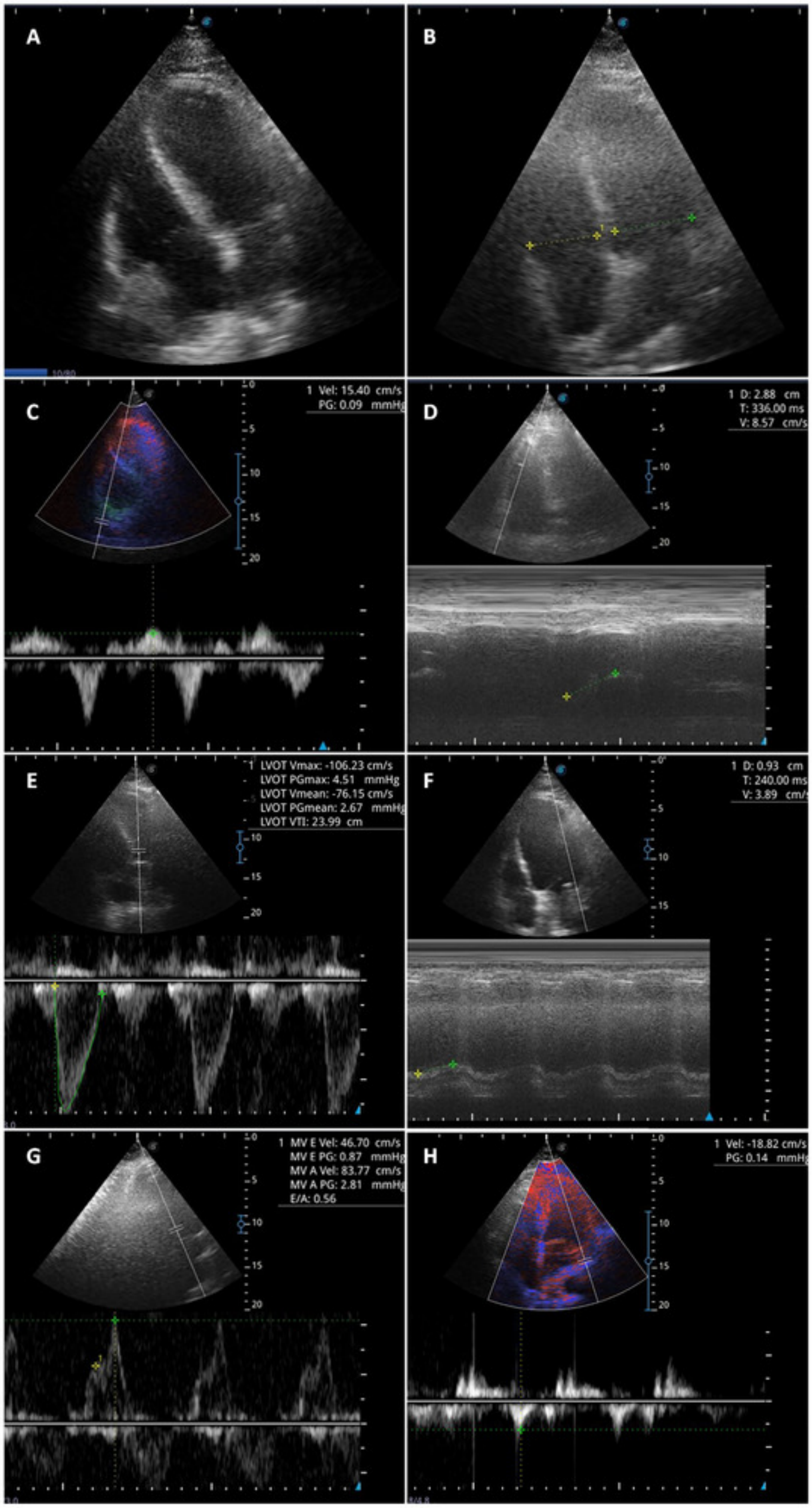

Prone positioning
oxygenation
Anterior chest wall compliance
Mechanical compression of Vascular beds
Intra-abdominal pressure
Intra-pleural pressure
Volume Status
Transpulmonary pressure
Adequate
Hypovolemic
PVR & RV afterload
Venous return and RV preload
Venous return and RV preload
LV preload and CO
LV preload and CO



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PG: 0.14 mmHg