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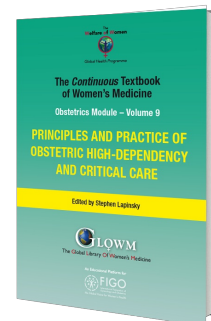
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Chapter

Hemodynamic Monitoring of the Critically Ill Obstetric Patient

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INTRODUCTION

The cardiovascular system during pregnancy undergoes changes that ensure fetal growth.¹ Understanding all the physiological changes of pregnancy to the cardiovascular system will allow a better interpretation of the hemodynamics in the obstetric patient. Hemodynamic monitoring involves the estimation of cardiac output (CO) and its variables: preload, contractility, and afterload,^{1,2,3,4} which enables selection of the most appropriate therapy (i.e. fluids or vasopressor). Currently, invasive and non-invasive monitoring systems are available. In the obstetric patient, non-invasive monitoring systems are preferred, and many of these have shown adequate correlation with invasive monitoring systems.

PHYSIOLOGICAL CHANGES IN THE CARDIOVASCULAR SYSTEM OF THE PREGNANT WOMAN

During pregnancy the cardiovascular system experiences changes to ensure fetal growth and to prepare the mother for childbirth and puerperium.¹ Cardiac output is calculated as the result of stroke volume and heart rate. Stroke volume is defined as the amount of blood pumped into the aorta during each cardiac cycle and depends on preload and afterload. During pregnancy, the blood volume increases, leading to an increment in the amount of blood returning to the heart (the preload). Also, afterload decreases due to vasodilation. The stroke volume, therefore, increases by 20–30% during

pregnancy.⁵ Maternal heart rate increases at the beginning of pregnancy, reaching its peak and plateau in the third trimester, this increase ranges from 15 to 20 beats per minute. As a result of the increase in stroke volume and maternal heart rate, cardiac output increases by 30–50% during pregnancy (from about 4.6 L/min to 8.7 L/min).⁶

Hemodynamically, there are three physiological patterns during pregnancy:

1. Continuous increase in cardiac output until term;⁷
2. Constant increase in cardiac output, reached its peak at the last half of pregnancy, with subsequent decrease at term;⁸ or
3. A constant increase in cardiac output, reaching a maximum in the second half of pregnancy, with a plateau near to term.⁶

Peripheral vascular resistance during pregnancy decreases. This decrease in systemic vascular resistance (SVR) is mediated by progesterone and nitric oxide, which relax the vascular smooth muscle. Nitric oxide is produced in the endothelium of blood vessels, and its production is regulated by estradiol during pregnancy.⁶ This reduction in SVR is more marked towards the 2nd trimester of pregnancy (nadir around 20 weeks of gestation), the uteroplacental circulation being responsible for 20–26% of the decrease in resistance. By the end of the third trimester, the systemic vascular resistance shows a plateau and then a slight increase towards delivery, returning to non-pregnant values at 2 weeks after delivery.⁸

Understanding the physiological changes of pregnancy on the cardiovascular system will allow a better interpretation of hemodynamic monitoring in the obstetric critically ill patient.¹ Variations in these physiological changes seem to be related to a higher incidence of maternal and fetal complications (gestational hypertension, pre-eclampsia, and intrauterine growth restriction).⁹

Some hemodynamic subtypes have been proposed in preeclamptic patients. One is a hyperdynamic profile (high CO and low SVR) characteristic of near-term pre-eclampsia, and the other a hypodynamic profile (low CO and high SVR) in preterm and early-onset pre-eclampsia. The latter profile is a more dangerous condition, closely related with not only worse maternal outcomes, but also fetal impairment including Intrauterine growth restriction (IUGR) and fetal loss.¹⁰

INDICATIONS FOR MONITORING IN THE OBSTETRIC PATIENT

Traditionally, the main indication for hemodynamic monitoring in the general population is circulatory compromise due to shock or hypoperfusion; in the obstetric patient, hemodynamic compromise may be manifest as hypotension or hypertension, as the result of conditions such as postpartum hemorrhage and sepsis causing hypotension (Table 1), but also the hypertensive disorders of pregnancy.

Table 1 Main causes of circulatory shock in the pregnant woman.

Hypovolemic shock	Ectopic pregnancy, placenta previa, postpartum hemorrhage, trauma, uterine rupture
Shock classification	Causes
Septic shock	Puerperal sepsis, septic abortion
Cardiogenic shock	Pre-existing valvular heart disease, peripartum cardiomyopathy
Obstructive shock	Pulmonary embolism, amniotic fluid embolism

Hemodynamic monitoring in the pregnant woman might help to:

1. Identify patients with the highest risk of maternal and fetal complications; and
2. Once circulatory shock has been established, to identify the hemodynamic problem and establish a specific therapy.

A decrease in cardiac output and an increase in resistance in the first stage of labor has been described as a risk factor for maternal–fetal complications, such as fetal compromise/hypoxia, postpartum hemorrhage or uterine atony, as a

consequence of a decrease in blood flow to the uterus.¹¹

HOW TO MONITOR?

The monitoring can be divided into:

1. Clinical monitoring: physical examination is essential (HR, respiratory rate, state of consciousness, urine output, skin perfusion, capillary refill time); however, changes in clinical variables appear late or may be attributed to physiological changes during pregnancy;
2. Biochemical monitoring: through laboratory markers of tissue perfusion (lactate; mixed venous oxygen saturation, SvO₂; veno-arterial blood CO₂ concentration difference, DCO₂; base deficit, BD); that establish the shock diagnosis without defining its etiology;
3. Hemodynamic monitoring (cardiac index, CI; cardiac output, CO; systemic vascular resistance, SVR): Mainly focused on changes in the cardiovascular system.³

Blood pressure measurement during pregnancy should be standardized. However, in severe cases and cases of blood pressure measurement in association with CO monitoring, blood pressure should be taken as closely as possible and in the same position as the CO assessment, to allow a reliable calculation.¹²

Blood pressure can be obtained invasively using intraarterial catheters or non-invasively using either a sphygmomanometer or automated oscillometric devices validated for use in pregnancy, using an appropriately sized arm cuff.¹³

MONITORING SYSTEMS

A variety of monitoring systems have been developed to monitor the cardiovascular system; these can be classified into invasive, minimally invasive or less invasive and non-invasive systems.¹¹

Invasive monitoring: pulmonary artery catheter

For decades, the pulmonary artery catheter (PAC) was used to measure cardiac output. It was first described in 1970, and for more than 20 years was considered the gold standard in terms of hemodynamic monitoring.¹⁴

Concerns regarding the risks of the pulmonary artery catheter in the non-pregnant as well as in obstetric patients has limited its use; however, usual complications (subclavian or jugular injury, pneumothorax, arrhythmias and cardiac trauma) are not greater in pregnant patients than in the general population.¹⁵ Currently, in most centers the use of pulmonary artery catheter in pregnancy is very limited.

Minimally or less invasively monitoring

Most of the minimally invasive monitoring systems are based on the arterial pressure waveform analysis, by integrating the area under the systolic part of the arterial curve. Some differences between the monitoring systems are the insertion site of the arterial line (central or peripheral), and the need for calibration. Currently, there are three such systems:

PiCCO and LiDCO (calibrated) and Flotrac (not calibrated).¹⁶

LiDCO

This technique is simple, requires the presence of an arterial line and central or peripheral venous access. For calibration, a small dose of lithium 0.3 mmol/L is injected; A lithium sensor generates a concentration-time curve at the level of the arterial line. The CO is calculated using the lithium dose and the area under the curve, before recirculation. Recent measurements of serum hemoglobin and sodium chloride are also required for calibration purposes and indexed values such as maternal height and weight.

Lithium is perfect for dilution of the indicator because it has no significant first-pass metabolism or loss in the

pulmonary circulation and is rapidly redistributed. Lithium dose has no pharmacological or toxic effect.¹⁷

PiCCO system (Pulsion Medical Systems)

This system uses a traditional transpulmonary thermodilution method to measure CO and pulse wave contour analysis to generate a continuous beat-to-beat measurement of the CO; it requires a central venous catheter and a central arterial line. PiCCO also provides valuable information about intrathoracic lung volumes and extracellular lung volumes, including intra thoracic blood volume (ITBV) and extravascular lung water (EVLW).¹⁸

FloTrac sensor and Vigileo monitor

This system uses a blood pressure wave analysis based on the principle that the aortic pulse pressure is proportional to the stroke volume and inversely proportional to the aortic compliance. This system has some limitation compared to LiDCO and PiCCO since it does not provide truly continuous data in real-time, analyzing a 20 second window of pressure waveforms.¹⁶

None of these systems has been validated in pregnancy, with few articles published in this population. Recently the LiDCO plus monitoring system was evaluated in normal pregnancy, providing high-quality information, and found to be easy to use and safe. The LiDCO plus system can guide fluid therapy without potential risks to the mother and the newborn.¹⁹

Hemodynamic parameters of minimally invasive monitoring systems (PiCCO)(Table 2) generated by these hemodynamic systems

1. Preload parameters:
 - a. Global volume at the end of diastole (GEDV)
 - b. Intrathoracic blood volume (ITBV)
 - c. Stroke volume variation (SVV)
 - d. Pulse pressure variation (PPV)
2. Afterload parameter:
 - a. Systemic vascular resistance (SVR)
3. Contractility variables:
 - a. Global ejection fraction (GEF)
 - b. Cardiac function index (CFI)
 - c. Maximum left ventricular contractility (dPmax)
4. Excess lung water parameter:
 - a. Extravascular lung water (EVLW)
 - b. Pulmonary vascular permeability index (PVPI)

Table 2 Hemodynamic parameters of the transpulmonary thermodilution system.

Variable	Definition	Reference range
Cardiac function index	The CFI is the ratio of the index of cardiac output to the index of the GEDV. A measure of how well the CO is doing in relation to its preload	CI = CO/CS (normal value: 3.0–5.0 l/min/m ²) CFI = CI/GEDV (normal value: 4.5–6.5 l/min)
Global end diastolic index	Is the volume of blood contained in the 4 chambers of the heart	GEDI – global end diastolic index: 680–800 ml/m ²
Intra thoracic blood volume index	Is the volume of the 4 chambers of the heart plus the blood volume in the pulmonary vessels	ITBVI – intra thoracic blood volume index: 850–1000 ml/m ²

Stroke volume Variable variation	Definition	Reference range
	Reflects the sensitivity of the heart to the cyclic changes in cardiac preload induced by mechanical ventilation. Can predict whether stroke volume will increase with volume expansion	SVV – stroke volume variation: <13%
Pulse pressure variation	The physiological principle is the same as in the SVV, but in this case the measure is the quotient between the difference of the maximum and minimum value of the pulse pressure by the average of the two values, expressed as a percentage, in the same respiratory cycle	PPV – pulse pressure variation: <13%
Systemic vascular resistance index	The systemic vascular resistance index (SVRI) represents the peripheral vascular resistance. It is calculated as the difference in gradient from the aorta to the right atrium and is inversely related to blood flow (IC)	SVRI – systemic vascular resistance index: 1700–2400 dyn/s/cm ⁵ /m ²
Extravascular lung water index	Is the amount of water content in the lungs or degree of pulmonary edema	ELWI – extravascular lung water index: 3–7 ml/kg
Pulmonary vascular permeability index	Indication of pulmonary edema in relation to preload. This helps to differentiate if an increase in ELWI is due to an increase in hydrostatic pressure or a consequence of alveolar–capillary membrane damage	PVPI 1–3

Adapted from reference¹⁶.

Variables such as SVV and PPV (dynamic variables), have a greater capacity to discriminate between fluids responder or non-responder patients; however, these have been validated mainly in patients receiving mechanical ventilation.²⁰

Non-invasive monitoring

The non-invasive monitoring systems can be classified into three groups:

1. Cardiac output monitoring based on measures of aortic blood flow:
 - a. Transthoracic echocardiography (TTE);
 - b. Transesophageal echocardiography (TEE);
 - c. Transesophageal Doppler;
 - d. Suprasternal Doppler.
2. Cardiac output monitoring based on changes in electrical resistance induced by vascular flow:
 - a. Bioimpedance and Bioreactance.
3. Cardiac output monitoring based on non-invasive blood pressure monitoring.⁶

Cardiac output monitoring based on measures of aortic blood flow

Transthoracic echocardiography

Transthoracic echocardiography (TTE) allows the calculation of cardiac output and the cardiac index. This evaluation is made with the patient in the supine position at 45°, in a slightly lateral left position. In the parasternal long axis (PLAX), cardiac output can be determined by the product of heart rate, the pulsed Doppler velocity time integral (VTI) and aortic cross-sectional area (AoCSA) or m-mode left ventricular dimensions during systole and diastole (LVED and LVES, respectively) and heart rate.⁴

The hemodynamic monitoring by transthoracic echocardiography has been compared with the reference standard (pulmonary artery catheter) in obstetric patients with sepsis, acute respiratory distress syndrome (ARDS) and pre-eclampsia, with an adequate correlation between the two methods.²¹ The response to fluids is evaluated by a 10–15% increase in cardiac output after a volume challenge, or by passive leg elevation.²²

Some authors suggest measurements of the inferior vena cava (IVC) to identify fluids responders and non-responders in spontaneous breathing patients. An IVC diameter <2.1 cm or a collapse >50% during inspiration suggests a right atrium

pressure approximately of 3 mmHg (0–5 mmHg), suggesting fluid responsiveness, while an IVC diameter >2.1 cm or a collapse <50% suggests a right atrium pressure of 10–20 mmHg.²³

TTE in conjunction with pulmonary ultrasound in severe pre-eclamptic patients, may help to guide therapy. This allows the identification of volume responsiveness (changes in stroke volume >10%) after a passive leg raising test, diastolic dysfunction (E/e' ratio), and increased extravascular lung water (B lines).²⁴

Also, echo allows a rapid and reliable hemodynamic evaluation of obstetric patients in critical condition, with a valuable information for an appropriate management.

Transesophageal echocardiography (TEE)

The value of transesophageal echocardiography (TEE) lies in its ability to visualize the heart and obtain information on filling pressures, ventricular and valvular dysfunction. Currently, obstetric patients often have a large number of comorbidities (morbid obesity, hypertension, coronary heart disease, diabetes, and liver dysfunction), that increase the risk of cardiovascular complications.²¹

TEE is useful for hemodynamic monitoring and management of refractory shock, even in maternal cardiac arrest, by accurately reflecting the direction and magnitude of changes in cardiac output in real time. TTE has been validated versus invasive monitoring in not only healthy, but also in critically ill, pregnant women with hypertensive disorders. However, evidence regarding TEE in pregnancy is limited. TEE has been used to determine not only the etiology, but also to guide resuscitation, impacting on survival.

TEE is valuable to determine the etiology and to address the therapy in refractory hypotension or cardiac arrest in obstetric patients.^{25,26} The cardiac output is calculated based on the aortic flow; the aortic diameter has been established from anthropometric measurements (weight, height, and age), with high accuracy in most cases.²⁷

Echocardiography is an excellent hemodynamic system, given its non-invasive nature and immediate availability. For this, echocardiography should be considered as the reference for the validation of other hemodynamic methods in pregnant women.²⁸

Ultrasonic Cardiac Output Monitor (USCOM)

The Ultrasonic Cardiac Output Monitor (USCOM, USCOM Ltd, NSW, Australia) monitoring system applies a continuous Doppler system through the suprasternal notch to obtain the integral trans-aortic or transpulmonary time velocity. The transducer is placed in the suprasternal notch or the parasternal interspace, and the Doppler transducer is directed towards the aortic outflow tract to acquire a spectral Doppler flow. Once the optimal flow profile is obtained, the screen freezes and the flow profiles are automatically tracked allowing the stroke volume to be calculated as the product of the integral velocity-time and the cross-sectional area of the chosen valve. The area of the aortic valve is determined from indexed regression equations based on anthropometric measurements. The cardiac output is calculated from the product of the heart rate and the stroke volume.²⁹

The USCOM monitoring system accurately measures blood flow, stroke volume, and cardiac output, regardless of whether the patient has sinus rhythm, atrial fibrillation, vasopressors, or intermittent ventilation. The hemodynamic monitoring by USCOM has been compared with the NICOM monitoring, showing an excellent correlation not only in normal pregnant woman, but also in the group of hypertensive patients.³⁰

Cardiac output monitoring based on changes in electrical resistance induced by vascular flow

Bioimpedance and bioactance

Transthoracic bioimpedance was the first non-invasive method used to monitor cardiac output and has been used in various obstetric conditions, with the advantage of being independent of the operator. However, bioimpedance is inaccurate in intensive care units (ICUs) and other settings where significant electrical noise and body motion exist, thus, it is not widely used.

On the other hand, bioactance is a user-friendly and straightforward non-invasive monitoring system, which has solved bioimpedance issues and is currently used to evaluate maternal hemodynamics, even in the outpatient setting.³¹ The use of bioactance has gained considerable interest recently, and its use in the obstetric population is growing.

Bioactance (Starling SV, former NICOM device, Cheetah Medical) uses four double electrode stickers placed around the

thorax. A high-frequency current is passed between the four outer electrodes, and the resulting voltages are recorded between the four inner electrodes. The relative phase shift and rate of change of phase between these signals are determined and used in the calculations of stroke volume. The phase shift in the detected signal is proportional to the pulsatile blood flow in the thorax and is highly correlated with the volume of aortic blood.

The stroke volume is calculated with the following formula: stroke volume = $dX/dt \times VET$, where dX/dt the maximum flow and VET the ventricular ejection time. The heart rate is obtained from an electrocardiography (ECG) signal detected from the electrodes, finally calculating the cardiac output by the formula: $CO = \text{stroke volume} \times \text{heart rate}$.^{2,3}

While echocardiography is a low-risk and non-invasive method of assessing CO and stroke volume, it requires expert training to acquire appropriate images and reading experience to estimate stroke volume and CO. In contrast, bioimpedance requires minimum training to obtain these data; in addition, there are device-specific reference ranges for stroke volume, cardiac output and SVR for the NICOM device in healthy pregnancy.^{2,8} A recent study compared bioimpedance and echocardiography in pregnant patients in three trimesters and found an adequate correlation only during the third trimester.³²

Cardiac output monitoring based on non-invasive blood pressure monitoring

A large number of undetectable episodes of hypotension can only be recognized with continuous monitoring of arterial blood pressure, and non-invasive systems such as the continuous non-invasive arterial pressure (CNAP) can be used. This system is a non-invasive method for measuring the continuous blood pressure waveform. The patient's blood pressure is recorded by the CNAP module using a double finger cuff with an integrated infrared (IR) light sensor and air chambers. This system allows continuous non-invasive monitoring of blood pressure with high reliability compared with an intra-arterial waveform analysis.³³

The CNAP monitor includes an application for pregnant women, including patients with pre-eclampsia. However, in some instances the continuous measurement of blood pressure is not reliable and/or is not possible, e.g. reduced peripheral blood flow (shock, hypothermia) or presence of arterial vascular diseases (arteriosclerosis, Raynaud's syndrome, endarteritis obliterans, advanced vascular diseases), among others.³⁴

CLINICAL CASE

A 22-year-old woman, with a 41-week pregnancy, without comorbidities, was admitted to the emergency department with cough and dyspnea; heart rate of 160/min, blood pressure of 140/90 mmHg, respiratory rate of 28/min and oxygen saturation of 79%. Thorax auscultation revealed bilateral crackles and wheezing, fetal heart rate was 141 bpm, arterial blood gases showed severe hypoxemia. Her oxygen saturation was <90% using a face mask with FiO_2 of 80%. The patient was intubated and transferred to the intensive care unit and invasive ventilation initiated. She developed hypotension, and vasopressors were infused. A minimally invasive monitoring (FloTracä, Edwards Lifescience), was initiated with the findings in Table 3.

Table 3 Case study – findings of minimally invasive monitoring

Variable	Reference range	Results
Cardiac index	3.0–5.0 l/min/m ²	CI 1.7 l/min/m ²
Global end diastolic index	680–800 ml/m ²	GEDI 950 ml/m ²
Stroke volume variation	≤13%	SVV 7%
Pulse pressure variation	≤13%	PPV 8%
Systemic vascular resistance index	1700–2400 dyn/s/cm ⁵ /m ²	SVRI 3770 dyn/s/cm ⁵ /m ²
Extravascular lung water index	3.0–7.0 ml/kg	ELWI 17.2 ml/kg

Pulmonary vascular permeability index Variable	1.0–3.0% Reference range	PVPI 2.0% Results
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PRACTICE RECOMMENDATIONS

- Hemodynamic monitoring in pregnant women can be performed at three levels: clinical monitoring, biochemical monitoring, and hemodynamic monitoring.
- Traditionally, non-invasive hemodynamic monitoring systems are preferred in pregnant women, demonstrating adequate correlation with invasive monitoring systems such as pulmonary artery catheters.
- Non-invasive monitoring of cardiac output is potentially useful in the obstetric patient to define the most appropriate therapy: administration of fluids, giving a vasopressor medication or an inotropic drug.
- In the obstetric patient hemodynamic compromise can manifest as hypotension or hypertension.
- The leading causes of hemodynamic instability in pregnant women are postpartum hemorrhage, sepsis, and hypertensive disorders.
- Most minimally invasive monitoring systems are based on the analysis of the arterial blood pressure waveform, and others use calibration by transpulmonary thermodilution.
- Minimally invasive monitoring systems analyze preload, afterload, and contractility parameters, as well as valuable information on intrathoracic lung volumes and extravascular pulmonary water (EVLW).
- The transthoracic echocardiogram allows a rapid and reliable hemodynamic evaluation of the obstetric patient in critical condition. However, it requires expert training to obtain images and to estimate the systolic volume and cardiac output.
- Bioreactance requires minimal training to obtain systolic volume, cardiac output and systemic vascular resistance (SVR).

CONFLICTS OF INTEREST

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