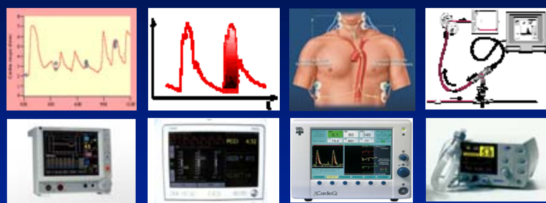
HEMODYNAMIC MONITORING: WHAT'S NEW?



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OBJECTIVES

- To discuss the need for hemodynamic monitoring in the critically ill patient
- To review the various techniques currently available for assessing hemodynamic function in the ICU
- To describe the relative merits and limitations of the various monitoring techniques

DISCLAIMERS

- I have no financial relationship with any company that produces hemodynamic monitoring equipment
- I will not be mentioning companies or products by name, but rather speaking about generic technologies
- Chances are that I will either not speak about your favorite technology or will have negative comments about it
- We are comparing technologies and their application in monitoring the sickest patients in our ICUs

WHY DO WE MONITOR?

- Preload, contractility, afterload, and oxygen transport are commonly abnormal in the critically ill
- Inadequate resuscitation and failure to restore cellular oxygen delivery and organ perfusion results in multiple system organ failure (MSOF) and death
- Optimization of cardiopulmonary function during critical illness reduces organ failure and improves survival
- Accurate assessment of hemodynamic function and goal-directed resuscitation is essential to improving patient outcome

CURRENT MONITORING TECHNOLOGIES

Invasive Monitoring Techniques
- Bolus thermodilution PAC
- Continuous thermodilution PAC
- Central venous oxygen saturation ($ScvO_2$)
- Arterial Pulse Contour Analysis

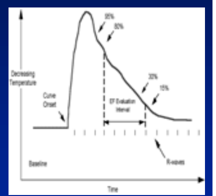
Noninvasive Monitoring Techniques
- Ultrasound
- Thoracic Electrical Bioimpedance
- Partial Carbon Dioxide Rebreathing

PULMONARY ARTERY CATHETER (PAC)

- Originally described by Swan & Ganz (1972)
- The "gold standard" for the next two decades
- Allows assessment of
  - Preload
    - Pulmonary artery occlusion pressure (PAOP)
    - Central venous pressure (CVP)
  - Contractility
    - Cardiac output (CO)
  - Afterload
    - Systemic vascular resistance (SVR)

INTERMITTENT THERMODILUTION

- CO is determined by measuring a "thermodilution curve" following injection of iced saline
- Accuracy is dependent upon multiple factors
  - Respiratory cycle
  - Injection technique
  - Regular heart rate
  - Proper catheter positioning
  - Transducer calibration
  - Accurate waveform interpretation
    - i.e., knowledgeable physician and nurse



THE LIMITATIONS OF THE PAC

- Requires an invasive right heart catheter
  - Risks of pneumothorax, hemothorax, arrhythmia, infection
- Use is based upon several assumptions:
  - Intermittent measurements reflect a patient's continuously changing hemodynamic state
  - PAOP & CVP accurately reflect end-diastolic volume
  - Ventricular compliance is unchanging

THE PAOP ASSUMPTION

Is ventricular geometry unchanged? | Is ventricular compliance unchanged? | Is there mitral valve disease? | Catheter properly positioned?

Preload = LVEDV = LVEDP = LAP = PAOP

Are intrathoracic or intra-abdominal pressures elevated?

PAOP is accurate ONLY when these potential sources of error have been minimized

IS THE PAC FLAWED OR ARE WE?

- The PAC has been subjected to greater scrutiny than any other monitoring technique
- Various studies have demonstrated that…
  - 47% of physicians cannot derive basic hemodynamic information from a PAC
  - 33% cannot identify a PAOP tracing
  - 33% cannot describe how to increase a patient's oxygen delivery
- Does it surprise anyone that prospective trials have failed to demonstrate a survival benefit with the use of this device?

BEFORE WE THROW OUT THE PAC

Conclusions

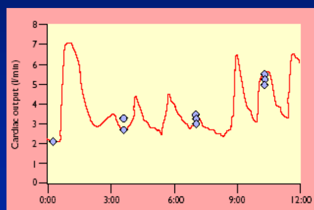
1. Significant deficits exist regarding fundamental concepts of hemodynamic monitoring and pulmonary artery catheterization
2. A PAC is a diagnostic tool and not a therapeutic intervention
3. The outcome of a patient with a PAC is altered only if management is guided by the data obtained
4. Our current concepts of PAC-related survival in the critically ill may be inaccurate

THE EVOLUTION OF THE PAC

- Mixed venous oximetry (SvO_2) (1980's)
  - Assessment of oxygen transport balance
- Volumetric technology (1990's)
  - Assessment of right heart function
    - Right ventricular ejection fraction (RVEF)
    - Right ventricular end-diastolic volume (RVEDV)
      - A volumetric, as opposed to pressure-based, estimate of intravascular volume status
      - Superior to PAOP & CVP in predicting preload recruitable increases in CO
  - Helps answer the important question
    - Volume or catecholamines?

ARE WE MISSING TOO MUCH?

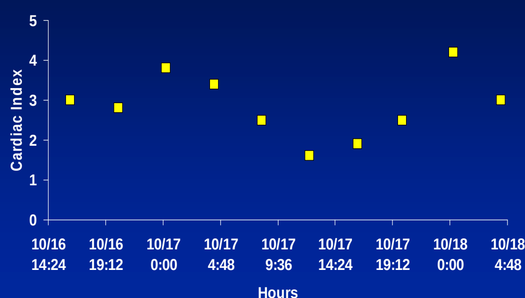
- Significant physiologic changes may go undetected by conventional intermittent monitoring techniques
  - A "snapshot" in time when a "moving picture" is what is needed



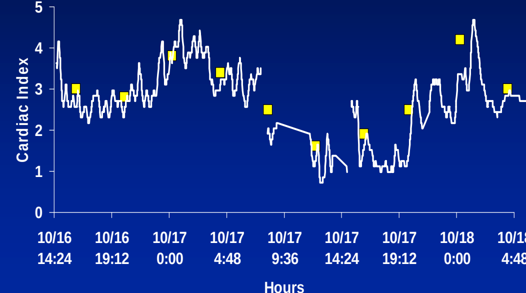
CONTINUOUS THERMODILUTION

- Utilizes pulsed thermal energy technology
- Provides an updated hemodynamic assessment every 60 seconds
- Reduces measurement variability
  - Automates CO measurement
  - Averages respiratory cycle variation
  - Standardizes injection technique
- Provides a constantly updated assessment of patient response to resuscitation leading to more efficient, goal-directed resuscitation

INTERMITTENT THERMODILUTION



CONTINUOUS THERMODILUTION



LIMITATIONS OF CONTINUOUS THERMODILUTION

- Accuracy may be decreased by
  - Irregular heart rate and/or rhythm
  - Mitral valve disease
  - Incorrect catheter placement
  - Hyperthermia (> 41° Celsius)
- Data obtained must guide interventions to justify the risk – benefit ratio of the PAC
- The patient outcome benefits are achieved at the cost of increased data complexity and intensivist time

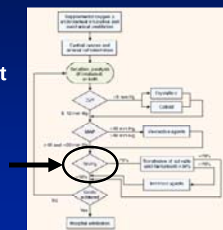
CONTINUOUS THERMODILUTION

- Most invasive and labor-intensive of the monitoring technologies demanding a thorough understanding of PAC monitoring principles
- Provides a continuous assessment of
  - preload (RVEDV, PAOP, CVP)
  - contractility (CO)
  - afterload (SVR, RVEF)
  - oxygen transport balance (SvO_2)

- Improves patient resuscitation and outcome
- Appropriate for the most critically ill patients

CENTRAL VENOUS OXYGEN SATURATION

- Restoration of oxygen transport balance is essential
- Central venous oxygen saturation ($ScvO_2$) monitoring allows continuous assessment of oxygen transport balance without a PAC
- $ScvO_2$ has gained widespread interest as a primary tool of EGDT and is advocated by the Surviving Sepsis Campaign



Rivers NEJM 2001

LIMITATIONS OF CENTRAL VENOUS OXYGEN SATURATION

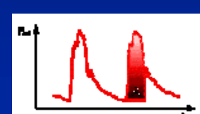
- Requires an invasive indwelling catheter
- Does not provide an accurate estimate of preload or a measurement of contractility
- SvO_2 and $ScvO_2$ are not equivalent
  - Trend in $ScvO_2$ over time, however, has significant clinical application and may represent one of the key features behind the success of EGDT

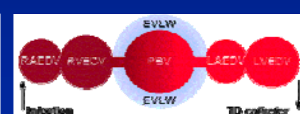
CENTRAL VENOUS OXYGEN SATURATION

- Provides a continuous assessment of
  - preload (CVP)
  - oxygen transport balance ($ScvO_2$)
- $ScvO_2$ is as simple as inserting a CVC, requires minimal interpretation, and may be initiated prior to ICU admission
  - Allows earlier assessment and resuscitation
- Expensive, but a useful early tool for identifying critical illness and beginning EGDT

ARTERIAL PULSE CONTOUR ANALYSIS

- Estimation of stroke volume from the arterial pressure waveform was first described almost 100 years ago
  - CO is proportional to the area under the arterial pressure waveform
- Proposed as a less invasive alternative to the PAC
- Requires only an arterial pressure catheter and a central venous catheter (CVC)





ARTERIAL PULSE CONTOUR ANALYSIS

- Three different technologies are currently available
  - Iced saline indicator calibration
  - Lithium indicator dilution calibration
  - Computer algorithm
- Two of these technologies require initial indicator dilution calibration
- All three technologies provide varying degrees of hemodynamic information

COLD SALINE CALIBRATION TECHNIQUE

- An initial CO is determined using iced saline thermodilution for calibration with subsequent measurements obtained using pulse contour analysis
- Provides continuous assessment of
  - Stroke volume (SV) and CO
  - Stroke volume variation (SVV)
    - Variation in beat-to-beat SV during a single respiratory cycle
- Provides intermittent assessment of
  - Global end-diastolic volume (GEDV)
  - Intrathoracic blood volume (ITBV)
  - Extravascular lung water (EVLW)

LIMITATIONS OF COLD SALINE CALIBRATION TECHNIQUE

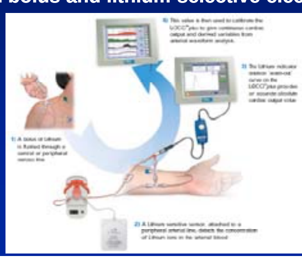
- Recalibration is necessary at least every 8 hours
- Not all measurements are continuous
- Accuracy is dependent upon
  - Arterial catheter location
    - Axillary / femoral more accurate than radial
  - Absence of aortic regurgitation, arrhythmias, intracardiac shunts, aortic aneurysms
  - Fully ventilated patient with stable heart rhythm

COLD SALINE CALIBRATION TECHNIQUE

- A less invasive alternative to a PAC
- Provides continuous assessment of
  - Preload (SVV)
  - Contractility (CO)
- Provides intermittent assessment of
  - Preload (GEDV, ITBV, EVLW)
  - Contractility (CO)
  - Afterload (SVR) (requires CVC for CVP)
- Can answer the "volume or catecholamine" question
- A viable option for minimally invasive continuous hemodynamic monitoring

LITHIUM INDICATOR DILUTION

- Utilizes pulse contour analysis via the patient's arterial catheter to measure CO, SV, and SVV
- Initial calibration is via indicator dilution using a lithium bolus and lithium-selective electrode



LITHIUM INDICATOR DILUTION

- Accuracy is dependent upon arterial resistance, compliance, and impedance
  - Initial calibration via indicator dilution is required
  - Recalibration is necessary every 8 hours
- The bedside monitor contains a variety of monitoring screens and assessment tools

LIMITATIONS OF LITHIUM INDICATOR DILUTION

- Cannot be used in patients on lithium therapy
- Lithium indicator is contraindicated in patients < 40 kg and during the first trimester of pregnancy
- Neuromuscular blocking agents can interfere with the lithium electrode
- Accuracy is dependent upon
  - Frequent recalibration
  - Arterial catheter location
  - Absence of aortic regurgitation, arrhythmias, intracardiac shunts, aortic aneurysms

LITHIUM INDICATOR DILUTION

- Another less invasive alternative to a PAC
- Provides continuous assessment of
  - preload (SV, SVV)
  - contractility (CO)
  - afterload (SVR) (requires CVC for CVP)
- Bedside monitor is very user-friendly
- A viable option for minimally invasive continuous hemodynamic monitoring

COMPUTER ALGORITHM

- **Utilizes pulse contour analysis via the patient's arterial catheter to measure CO, SV, and SVV**
- **Can also measure SvO_2 or $ScvO_2$ if appropriate catheters are in place**
- **Does not require indicator dilution for initial calibration**
  - **Utilizes a computer algorithm based upon pulse pressure and a mathematical model for vascular tone based upon patient gender, height, weight, and BSA**

COMPUTER ALGORITHM

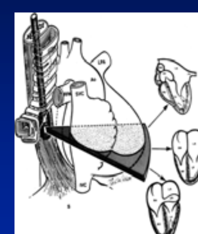
- **Accuracy is dependent upon arterial resistance, compliance, and impedance**
- **Provides a continuously updated CO, SV, and SVV every 20 seconds**
- **Currently requires that the patient is mechanically ventilated and without significant arrhythmias**

COMPUTER ALGORITHM

- **Another less invasive alternative to a PAC**
- **Provides continuous assessment of**
  - **preload (SV, SVV)**
  - **contractility (CO)**
  - **oxygen transport (SvO_2, $ScvO_2$)**
- **A viable option for minimally invasive continuous hemodynamic monitoring**

ULTRASOUND

- **Several different methods exist for applying ultrasound to hemodynamic monitoring**
  - **2-D echocardiography**
    - **Transthoracic**
    - **Transesopheageal (TEE)**
  - **Esophageal Doppler**
  - **Transcutaneous ultrasound**



2-D ECHOCARDIOGRAPHY

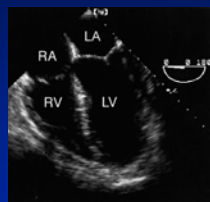
- **Provides information of cardiac structure and mechanical function**
- **Useful for assessing valvular anatomy and function as well as for aortic injury**
- **Can identify the presence of pericardial fluid**
- **Useful for assessing preload and contractility**

LIMITATIONS OF 2-D ECHOCARDIOGRAPHY

- **Both**
  - **Not a continuous monitoring technology**
- **Transthoracic (TTE)**
  - **10-40% failure rate in ICU due to patient anatomy**
- **Transesopheageal (TEE)**
  - **Requires a sedated patient; may require neuromuscular blockade**
  - **Contraindicated in patients with esophageal disease or difficult airway**

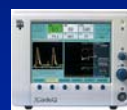
2-D ECHOCARDIOGRAPHY

- An alternative to a PAC
  - Arguably invasive
- Provides information not available with other techniques
- Provides assessment of
  - preload (LVEDV, LVEDA)
  - contractility (CO, LVEF)
  - valve function
  - pericardial fluid
- An essential technology for intermittently assessing the critically ill patient



ESOPHAGEAL DOPPLER

- First described as a method for measuring CO in 1971
- Based upon measurement of blood flow velocity in the descending aorta
  - Requires either measurement or estimation of cross-sectional aortic diameter



ESOPHAGEAL DOPPLER

- Provides "continuous" assessment of
  - SV and CO
  - Corrected flow time (FTc)
    - A preload estimate superior to PAOP and CVP in predicting preload recruitable increases in CO
  - Peak flow velocity
    - An estimate of ventricular contractility
  - Total SVR
    - Estimated SVR based on aortic blood flow
- Generally feasible only for short-term, intermittent monitoring

LIMITATIONS OF ESOPHAGEAL DOPPLER

- Proper positioning of the Doppler probe is essential
- There is a learning curve
  - Operator technique and experience directly impact upon measurement accuracy
- Requires a sedated or intubated patient
- May not be appropriate for patients with
  - Severe agitation
  - Bleeding diatheses
  - Esophageal varices
  - Aortic dissection

ESOPHAGEAL DOPPLER

- An alternative to a PAC
  - Arguably invasive
- Provides continuous assessment of
  - preload (SV, FTc)
  - contractility (CO, peak flow velocity)
  - afterload (estimated) (TSVR)
- A viable option for intermittent hemodynamic assessment or screening patients for hemodynamic abnormalities

TRANSCUTANEOUS ULTRASOUND

- Utilizes continuous wave Doppler ultrasound coupled with specialized algorithms and signal processing to non-invasively assess hemodynamic function
- A portable monitor allows measurements in a variety of clinical settings

TRANSCUTANEOUS ULTRASOUND

- Provides “continuous” assessment of
  - SV
  - CO
  - SVV
  - Corrected flow time (FTc)
  - Peak flow velocity
  - SVR
- Feasible for short-term, intermittent monitoring

LIMITATIONS OF ULTRASOUND

- Proper positioning of the transducer is essential
- There is a learning curve
  - Operator technique and experience directly impact upon measurement accuracy
- Accuracy may be limited in the presence of:
  - Subcutaneous air or bone
  - Obesity
  - Valvular abnormalities
  - Significant respiratory disease

TRANSCUTANEOUS ULTRASOUND

- A noninvasive alternative to a PAC
- Provides continuous assessment of
  - preload (SV, SVV, FTc)
  - contractility (CO, peak flow velocity)
  - afterload (SVR) (requires CVC)
- A viable option for intermittent hemodynamic assessment or screening patients for hemodynamic abnormalities

TECHNOLOGY COMPARISON:

INVASIVENESS ↑

Technology	Preload	Contractility	Afterload	O_2 Trans	Cost
Continuous TD	PAOP, CVP, RVEDV	CO, RVEF	SVR	SvO_2	$$$
Bolus TD	PAOP, CVP	CO	SVR		$
$ScvO_2$				$ScvO_2$	$$
Cold Saline	GEDV, SVV	CO	SVR		$$
Lithium Dilution	SVV	CO	SVR		$$$
Computer Alg	SVV	CO	SVR	$ScvO_2$	$$
TTE / TEE	LVEDV	CO			$
Esoph Doppler	FTc	CO			$
Transcut Ultrasound	FTc, SVV	CO	SVR		$$
Bioimpedance	SV	CO	SVR		$$$
Partial Rebreathing		CO			$$

CONCLUSIONS

- The currently available monitoring technologies vary in the cost and diversity of information provided
- The more invasive techniques generally provide the most accurate and comprehensive data
- Critically ill patients may benefit from the more invasive techniques as a result of the greater breadth of information gained
- Physicians must thoroughly understand the hemodynamic data obtained and utilize it in a goal-directed fashion if the monitoring technology is to improve patient outcome