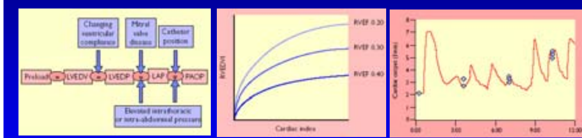
HEMODYNAMIC MONITORING: PART II CONTINUOUS CARDIAC OUTPUT



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IN THE LAST LECTURE…

- We monitor patients to
  - Guide therapeutic interventions
  - Allow early detection of organ dysfunction in order to avoid organ failure
  - Identify the need for changes in treatment strategy
- Cardiac performance can be assessed and therapeutic interventions directed using simple physiologic equations
- Traditional intracardiac filling pressures (ie., PAOP and CVP) are inaccurate in the critically ill surgical patient

POTENTIAL SOURCES OF ERROR IN THE PAOP ASSUMPTION

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

Preload = LVEDV = LVEDP = LAP = PAOP

Are intrathoracic or intra-abdominal pressures elevated?

PAOP and CVP are accurate ONLY when these potential sources of error have been eliminated

VOLUMETRIC VARIABLES

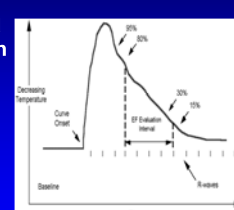
- Volumetric technology allows measurement of
  - Right ventricular ejection fraction (RVEF)
  - Right ventricular end-diastolic volume index (RVEDV)
- RVEDVI can be used as an estimate of intravascular volume or "preload" status
- RVEDVI is independent of zero-pressure references and changing ventricular compliance
  - It is unaffected by the majority of potential sources of error which plague PAOP and CVP

INTERMITTENT CO TECHNOLOGY

- Cardiac output (CO) is traditionally determined by the "thermodilution technique"
  - Iced saline is injected into the right atrium
  - The temperature of the blood flowing past a thermistor on the tip of the PAC is measured
  - A "thermodilution curve" is created
- If CO is high, the cold saline flows through the heart quickly and blood temperature returns to normal as the saline bolus rapidly moves through the heart
- If CO is low, blood flow is slower and blood temperature remains lower longer

THERMODILUTION CURVE

- As the iced saline bolus flows through the right atrium and ventricle, the intracardiac blood temperature decreases and then returns to normal
- The area under the curve determines the CO
- Accuracy is dependent upon multiple factors
  - Respiratory cycle
  - Injection technique
  - Regular heart rate / stable CO



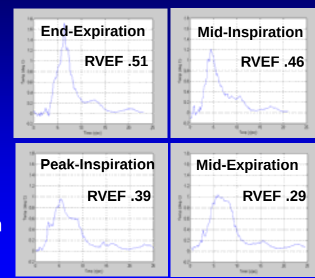
INTERMITTENT VOLUMETRIC TECHNOLOGY

- In the early 1990's, volumetric PAC's were introduced capable of measuring beat-to-beat temperature changes
- Required a modified PAC
  - Rapid response thermistor
    - To detect changes in temperature rapidly
  - Intracardiac electrodes
    - To determine heart rate using the R-R interval
  - Multi-hole injectate port
    - To ensure more thorough mixing of the injected saline in the right atrium

INTERMITTENT VOLUMETRIC TECHNOLOGY

Two problems remained

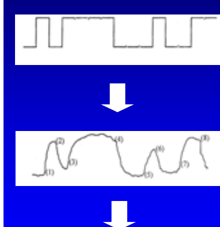
1. RVEF varies with the respiratory cycle and timing of injection
2. Intermittent measurements provide only a "snapshot" of the cardiac function when a "moving picture" is needed



CONTINUOUS CO TECHNOLOGY

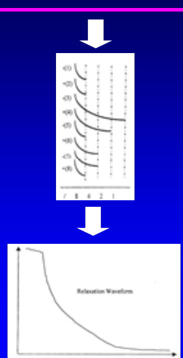
- In the early 2000's, continuous CO measurements became available
  - Utilizes continuous pulsed thermal energy instead of intermittent iced saline
- Reduces measurement variability
  - Averages respiratory cycle variation
  - Standardizes "injection" technique
  - Eliminates inconsistency associated with irregular heart rates
- Promotes improved resuscitation by providing a constantly updated CO assessment not previously available

CONTINUOUS CO TECHNOLOGY



- A wire coil on the surface of the PAC heats (rather than cools) the blood in the right atrium
- Energy to the coil is turned on and off in a pseudo-random pattern
- Pulmonary artery blood temperature is measured continuously

CONTINUOUS CO TECHNOLOGY



- By correlating the changes in blood temperature with when the thermal coil was heated, a series of thermal curves are generated
- These curves are combined mathematically to construct a traditional thermodilution curve
- Beat-to-beat temperature changes allow determination of stroke volume (SV), RVEDVI, and RVEF as well as CO

CASE PRESENTATION

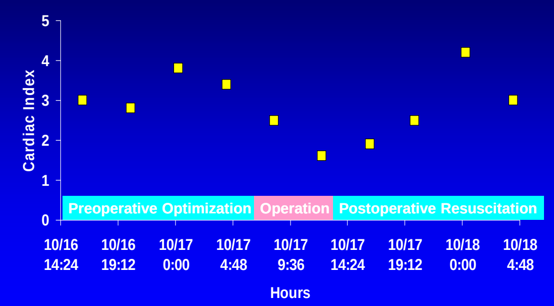
- 76 year old male with claudication
  - Past medical history
    - Hypertension
    - Coronary artery disease
    - Congestive heart failure
    - Diabetes mellitus

- Arteriogram — Aortoiliac occlusive disease
- Procedure — Preoperative optimization; Aortobifemoral bypass graft

PREOPERATIVE OPTIMIZATION

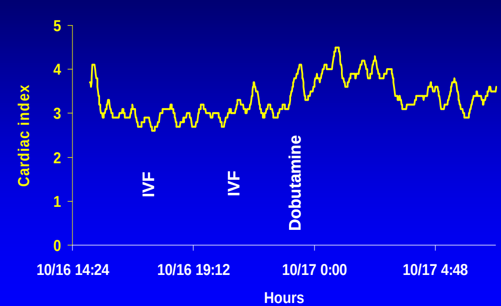
- A volumetric PAC is placed the day prior to operation in high risk patients
- Patient response to fluids and vasoactive medications is assessed
- Cardiopulmonary function is optimized in an attempt to reduce morbidity and mortality
- Patient resuscitation is continued postoperatively

INTERMITTENT METHODOLOGY

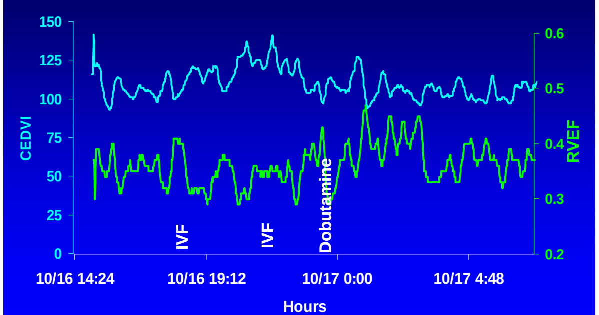


CONTINUOUS VOLUMETRIC TECHNOLOGY

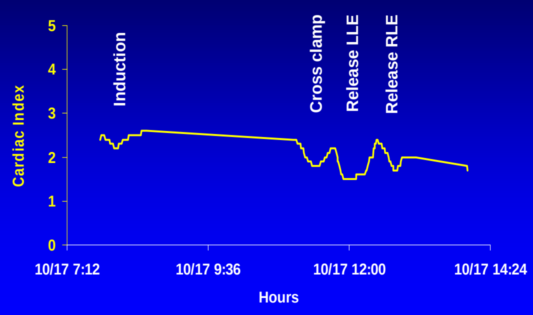
PREOPERATIVE OPTIMZATION



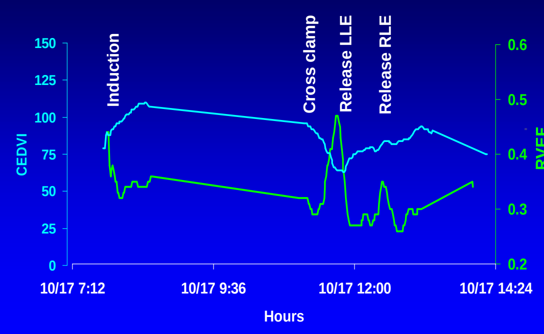
PREOPERATIVE OPTIMZATION



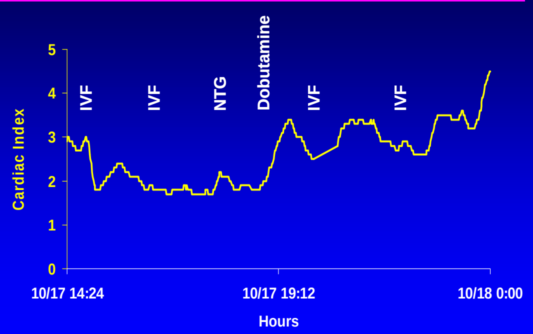
INTRAOPERATIVE COURSE



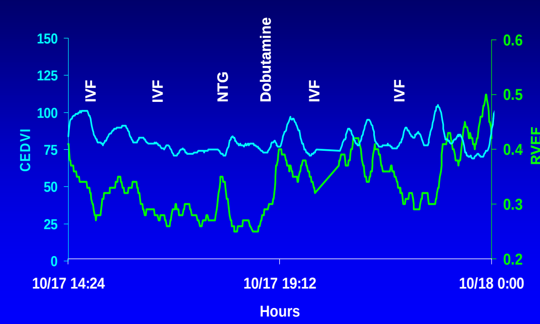
INTRAOPERATIVE COURSE



POSTOPERATIVE RESUSCITATION



POSTOPERATIVE RESUSCITATION



BENEFITS OF VOLUMETRIC TECHNOLOGY

- **The previous graphs demonstrate that significant physiologic changes go undetected by conventional intermittent monitoring technologies**
- **Patient response to interventions is immediately apparent using continuous CO monitoring**
- **Patient resuscitation is much more efficient and goal-directed**

THE VALUE OF RVEF AND RVEDVI

- **Numerous studies have demonstrated the value of volumetric measurements in resuscitation of the critically ill**
  - **Diebel et al. 1992, 1994, 1997**
  - **Eddy et al. 1994**
  - **Chang et al. 1995, 1996, 1998**
  - **Cheatham et al. 1994, 1998, 1999**

THE VALUE OF RVEF AND RVEDVI

- RVEDVI is a valuable indicator of resuscitation adequacy in the following patient populations
  - General / vascular surgery
  - Trauma
  - Burns
  - Sepsis
  - Acute respiratory distress syndrome (ARDS)
  - Intra-abdominal hypertension (IAH)
  - Abdominal compartment syndrome (ACS)

RVEF TECHNOLOGY

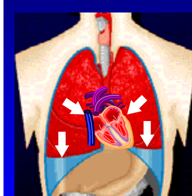
- RVEF was originally intended to estimate the contractility of the right ventricle
  - RVEF is too dependent upon afterload and the right ventricle too weak to maintain contractility
    - Increased afterload decreases RVEF
- RVEF, however, allows calculation of the right ventricular end-diastolic volume index (RVEDVI)
    - A volumetric as opposed to pressure-based assessment of preload

$$RVEDVI = \frac{SVI}{RVEF} = \frac{CI}{HR \times RVEF}$$

VOLUMETRIC VARIABLES

- RVEDVI is independent of pressure references and is not confounded by
  - Changing compliance
  - Elevated intra-thoracic pressure
  - Elevated intra-abdominal pressure
- RVEDVI can be confounded by
  - Irregular heart rate and/or rhythm
  - Mitral valve disease
  - Incorrect catheter placement

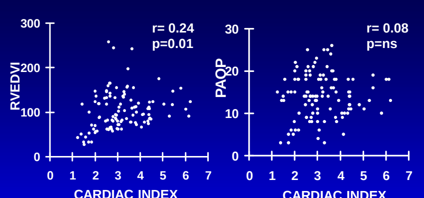
INTRATHORACIC PRESSURE



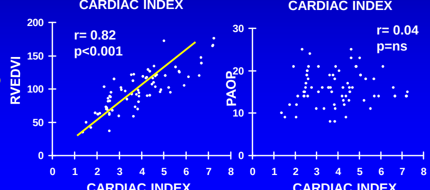
- Positive end-expiratory pressure (PEEP) has a number of effects on the heart and lung
  - Decreases venous return
  - Decreases CO
  - Increases SVR
  - Decreases pulmonary compliance
  - Increases intrathoracic pressure
- ARDS and IAH / ACS also result in increases in intrathoracic pressure that can affect cardiac function

RVEDVI IN ARDS

PEEP 5 cm H_2O



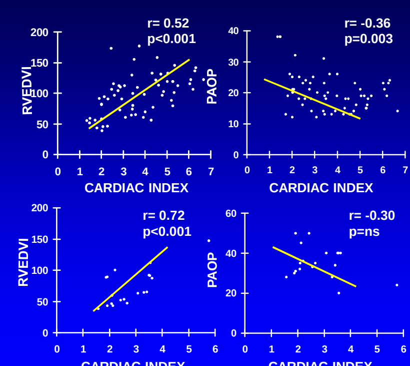
PEEP 6-14 cm H_2O



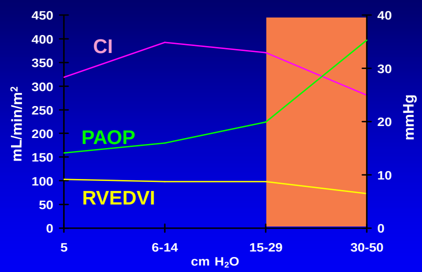
RVEDVI IN ARDS

PEEP 15-29 cm H_2O

PEEP 30-50 cm H_2O



HEMODYNAMIC EFFECTS OF ARDS



- PAOP provides contradictory information concerning preload status
- The negative effects of PEEP are typically not seen until > 15 m H_2O

RVEDVI AND ARDS

- PAOP provides erroneous information that may lead to inappropriate patient interventions
- RVEDVI is a superior predictor of preload status in patients on PEEP
- Volumetric PA catheters are indicated in any patient with ARDS and those who require PEEP > 15 cm H_2O
- Each patient requires resuscitation to optimize CO and tissue perfusion rather than to an arbitrary PAOP value

Cheatham et al. Crit Care Med 1998

ABDOMINAL COMPARTMENT SYNDROME

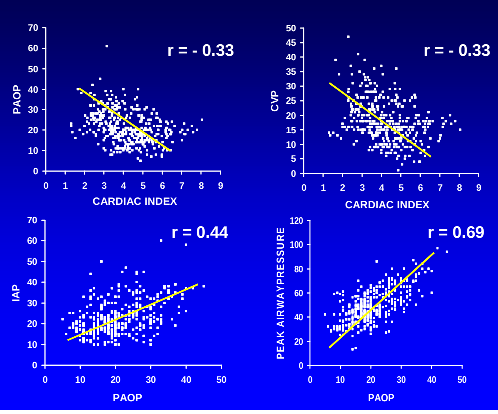
- Characterized by the presence of IAH and one or more of the following signs:

  - Oliguria
  - Abdominal distention
  - Refractory oliguria
  - Elevated airway pressures
  - Hypercarbia
  - Hypoxemia
  - Refractory metabolic acidosis
  - Elevated intracranial pressure

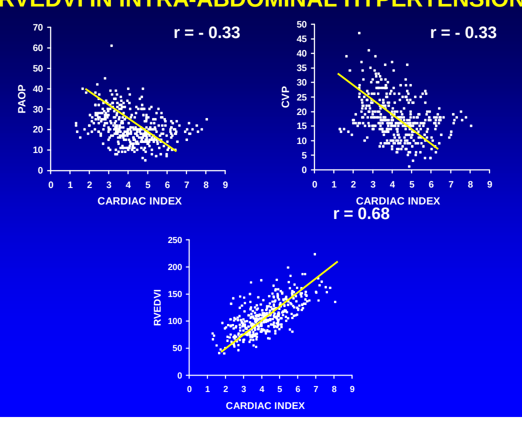
HEMODYNAMIC MONITORING IN IAH/ACS

- Increased intra-abdominal or intrathoracic pressure elevates intracardiac pressures by an amount that is unpredictable
- Use of PAOP and CVP in patients with IAH may lead to inappropriate therapy
- RVEDVI is a more accurate estimate of intravascular volume status than PAOP in patients with IAH / ACS

RVEDVI IN INTRA-ABDOMINAL HYPERTENSION



RVEDVI IN INTRA-ABDOMINAL HYPERTENSION



CORRELATION WITH CI

Variable	r	p
RVEDVI	0.69	<0.0001
PAOP	- 0.33	<0.0001
CVP	- 0.32	<0.0001
PIP	- 0.30	<0.0001
Paw	- 0.16	0.02
IAP	- 0.05	0.40
PEEP	- 0.04	0.53

Cheatham et al. J Trauma 1998

HEMODYNAMIC MONITORING IN IAH / ACS

- CI correlates significantly better with RVEDVI than with PAOP or CVP
- PAOP and CVP provide erroneous information and may lead to inappropriate therapy
- RVEDVI is a superior predictor of patient response to fluid challenge
- Right ventricular function PAC's are the catheter of choice in patients with IAH / ACS

RVEDVI AS A PREDICTOR OF SURVIVAL

- Several studies have demonstrated improved patient outcome with the use of volumetric PAC's
  - RVEDVI > 110 mL/m2 (RVEF 0.39) (Miller)
    - Decreased MSOF and death
  - RVEDVI > 120 mL/m2 (RVEF 0.34) (Chang)
    - Improved visceral perfusion
    - Decreased organ dysfunction and failure
  - RVEDVI > 130 mL/m2 (RVEF 0.37) (Cheatham)
    - Improved survival from IAH / ACS

"OPTIMAL" RVEDVI

- Initial studies suggested that an RVEDVI of 130-140 mL/m^2 was optimal
  - This oversimplifies what is actually a complex and dynamic relationship
- RVEDVI and RVEF are "mathematically coupled"
  - RVEF must be taken into consideration when assessing the adequacy of RVEDVI

$$RVEDVI = SVI / RVEF \cong 1 / RVEF$$

KEY POINTS TO INTERPRETING RVEF & RVEDVI VALUES

1) RVEDVI reflects preload status

2) RVEF reflects contractility and afterload

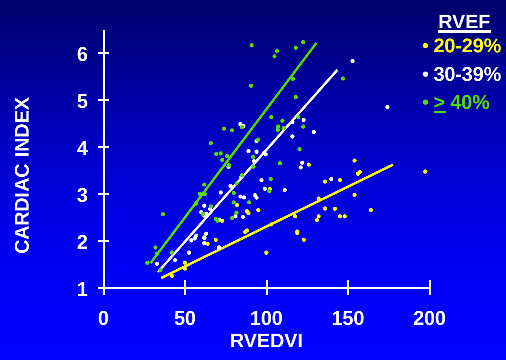
3) Ventricular contractility and compliance are constantly changing (Eddy 1995)

4) For a given preload status, as RVEF changes, RVEDVI must also change

KEY POINTS TO INTERPRETING RVEF & RVEDVI VALUES

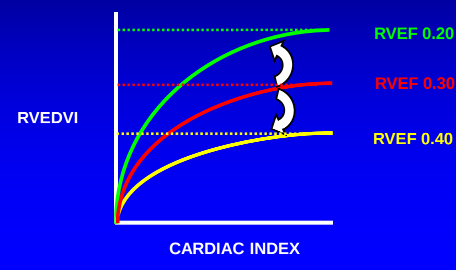
RVEDVI must be interpreted in conjunction with RVEF

"FAMILIES" OF STARLING CURVES



"FAMILIES" OF STARLING CURVES

- As RV contractility changes, patients move to a new Starling curve and the target RVEDVI must change



"RVEF CORRECTED" RVEDVI

	"Optimal" RVEDVI	
RVEF	Normal	Critically ill
.20	200 mL/m²	240 mL/m²
.30	150 mL/m²	180 mL/m²
.35	125 mL/m²	150 mL/m²
.40	100 mL/m²	120 mL/m²
.50	50 mL/m²	60 mL/m²

CONCLUSIONS

- Critically ill patients can have widely disparate levels of ventricular function
- Optimal RVEDVI, PAOP, or CVP values must be determined for each individual patient
- RVEDVI is superior to PAOP or CVP in determining preload recruitable increases in CI
  - Especially true when cardiac filling pressure interpretation is confounded by conditions such as shock, ARDS, and ACS

CASE STUDIES

The following are a series of patient scenarios that illustrate the key points from the Hemodynamic Monitoring lectures

HEMODYNAMIC VARIABLES

Preload	Contractility	Afterload
PAOP	CI	SVRI
CVP	LVSWI*	PVRI
RVEDVI	RVSWI*	
SVI	RVEF	RVEF

* Assumes preload and afterload optimized

PATIENT 1

- 74 yo male 2 weeks S/P ABF bypass
  - PMH: CAD, MI x 2, NIDDM
- Initially seen at an outside hospital with hypotension, abdominal pain, low UOP
- Transferred to ICU via helicopter on dopamine
- Surgeon diagnoses ischemic left colon and plans exploratory laparotomy; requests preop evaluation
- Indications for PA catheter:
  - Pre-operative optimization

PREOPERATIVE OPTIMIZATION GOALS

CI	> 2.5 L/min/m²
LVSWI	> 40 (g-m/m²)
Ca-vO_2	< 5.5 mL O_2/ dL blood
DO_2I	> 600 mL O_2/m²
VO_2I	> 170 mL O_2/m²
RVEDVI	> 100 mL/m²
RVEF	> 0.40

These parameters are discussed in the "Oxygenation Parameters" lecture. You may want to come back and review these cases again after reviewing that lecture.

PATIENT 1

Parameter	09:51
CI (L/min/m²)	2.6
HR (beats/min)	109
LVSWI (g-M/m²)	15
RVEF (fraction)	0.28
RVEDVI (mL/m²)	83
PAOP (mmHg)	15
SVRI (dyne·sec·cm⁻⁵/m²)	1683
SvO_2 (fraction)	0.69
DO_2I (mL O_2/m²)	423
VO_2I (mL O_2/m²)	125
Urine output (mL/hr)	10

Q: What therapeutic changes should be implemented?

A: The patient's UOP and RVEDVI both suggest hypovolemia. The patient's CI, RVEF, and LVSWI suggest decreased contractility. This should always be corrected first by ensuring adequate preload.

PATIENT 1

Parameter	09:51	10:49
CI	2.6	4.3
HR	109	102
LVSWI	15	40
RVEF	0.28	0.42
RVEDVI	83	130
PAOP	15	10
SVRI	1683	1083
SvO_2	0.69	0.73
DO_2I	423	710
VO_2I	125	217
Urine output	10	40

1000 mL IVF

1000 mL of IVF is administered and the patient's UOP and RVEDVI respond.

Q: What therapeutic changes should be implemented now?

A: The patient's preload is adequate, but afterload (SVRI) has fallen. The patient meets the preoperative optimization goals and is allowed to go to the operating room.

PATIENT 1

Parameter	10:49	17:15
CI	4.3	2.6
HR	102	92
LVSWI	40	18
RVEF	0.42	0.37
RVEDVI	130	76
PAOP	10	23
SVRI	1083	1764
SvO_2	0.73	0.61
DO_2I	710	458
VO_2I	217	139
Urine output	40	110

2900 mL IVF
500 mL EBL
250 mL UOP

The patient goes to the operating room and returns with the parameters listed.

Q: What therapeutic changes should be implemented now?

A: The patient's preload is inadequate and the SVRI has increased to compensate given the hypovolemia. Further fluid resuscitation is indicated as the patient has responded well to this previously.

PATIENT 2

- 18 yo male with bilateral femur fractures following a MVC
- Admitted to ICU for acute respiratory failure 12 hours following intramedullary nailing of his femurs
  - Progressive ARDS requiring PEEP / FiO2
    - "Pulmonary fat emboli syndrome"
  - Blood loss requiring fluid resuscitation
- Indications for PA catheter
  - Refractory shock
  - Progressive ARDS

PATIENT 2

Parameter	#1
CI (L/min/m²)	2.1
HR (beats/min)	140
RVEF (fraction)	.43
RVEDVI (mL/m²)	60
PAOP (mmHg)	12
PEEP (cm H_2O)	10
FiO_2 (fraction)	.40
UOP (mL/hr)	10

Q: What therapeutic changes should be implemented?

A: The patient's preload is inadequate as evidenced by the tachycardia and low UOP and RVEDVI. Fluid resuscitation is indicated.

PATIENT 2

Parameter	#1		#2
CI	2.1		2.9
HR	140		110
RVEF	.43		.38
RVEDVI	60	2000 mL IVF →	97
PAOP	12		15
PEEP	10		10
FiO_2	.40		.40
UOP	10		50

The patient is given 2000 mL of normal saline.

Q: What therapeutic changes should be implemented now?

A: Although the patient's UOP has improved, his CI, RVEF, and RVEDVI remain low. His PAOP is 15, but he is on PEEP of 10 cm H_2O making his transmural "true" PAOP less than that. As is common for such patients, he still needs more fluid.

PATIENT 2

Parameter	#1	#2		#3
CI	2.1	2.9		3.5
HR	140	110		90
RVEF	.43	.38		.42
RVEDVI	60	97	1000 mL IVF →	122
PAOP	12	15		15
PEEP	10	10		10
FiO_2	.40	.40		.40
UOP	10	50		60

The patient is given another 1000 mL of IVF.

Q: What therapeutic changes should be implemented now?

A: The patient's CI, HR, RVEF, RVEDVI, and UOP are improving. You elect to monitor his progress.

Six hours later, his SaO2 slowly drops to 0.90. What intervention is appropriate at this time?

PATIENT 2

Parameter	#3		#4
CI	3.5		2.4
HR	90		120
RVEF	.42		.28
RVEDVI	122	PEEP →	87
PAOP	15		25
PEEP	10		18
FiO_2	.40		.60
UOP	60		5

You increase the PEEP serially to 18 cmH_2O and FiO_2 to 0.60. His ARDS is worsening with a chest x-ray showing bilateral patchy infiltrates. His UOP has fallen.

Q: What therapeutic changes should be implemented now?

A: The increased intrathoracic pressure is impeding venous return to the heart. Further IVF is warranted.

PATIENT 2

Parameter	#3		#4		#5
CI	3.5		2.4		3.1
HR	90		120		105
RVEF	.42		.28		.30
RVEDVI	122	PEEP →	87	IVF →	115
PAOP	15		25		27
PEEP	10		18		18
FiO_2	.40		.60		.50
UOP	60		5		35

With IVF administration, his CI, HR, RVEDVI, and UOP all improve. RVEF remains decreased due to the increased right ventricular afterload from ARDS and PEEP.

PATIENT 3

- 25 yo male S/P GSW to inferior vena cava
- Transferred to ICU following "damage control laparotomy" for ongoing hemorrhage
  - "Bogota bag" in place covering the open abdomen
- Patient remains hypotensive with elevated arterial lactate and low urinary output
- Indications for PA catheter
  - Refractory shock
  - Oliguria

PATIENT 3

Parameter	#1
CI (L/min/m²)	2.3
HR (beats/min)	150
RVEF (fraction)	.38
RVEDVI (mL/m²)	43
PAOP (mmHg)	5
IAP (mmHg)	15
PIP (cm H_2O)	36
UOP (mL/hr)	2

Q: What therapeutic changes should be implemented?

A: The patient's preload is inadequate as noted by the low CI, RVEDVI, PAOP, and UOP. His IAP is moderately high and will needed to be watched closely. Fluid resuscitation is needed.

PATIENT 3

Parameter	#1		#2
CI	2.3		2.5
HR	150		120
RVEF	.38		.31
RVEDVI	43	1000 mL IVF →	53
PAOP	5		18
IAP	15		22
PIP	36		52
UOP	2		10

1000 mL of saline is given, but minimal response is seen.

Q: What therapeutic changes should be implemented now?

A: The patient's preload remains inadequate. His PAOP, IAP, and PIP are all rising rapidly. You recommend revision of the patient's Bogota bag, but the surgeon says he doesn't believe abdominal compartment syndrome is present.

PATIENT 3

Parameter	#1		#2		#3
CI	2.3		2.5		1.8
HR	150		120		160
RVEF	.38		.31		.25
RVEDVI	43	IVF →	53	IVF →	49
PAOP	5		18		30
IAP	15		22		35
PIP	36		52		87
UOP	2		10		0

You give additional saline to try and improve visceral perfusion. IAP and PIP continue to rise. You call the surgeon back and inform him of the patient's recurrent ACS

Q: What therapeutic changes should be implemented now?

A: The patient needs immediate abdominal decompression for his severe ACS.

PATIENT 3

Parameter	#3		#4
CI	1.8		2.9
HR	160		105
RVEF	.25		.42
RVEDVI	49	Exp Lap →	108
PAOP	30		16
IAP	35		14
PIP	87		48
UOP	0		50

The surgeon reluctantly reopens the abdomen and finds ongoing bleeding. This is controlled and a larger Bogota bag is placed.

Q: What therapeutic changes should be implemented now?

A: The patient is still hypovolemic (low CI and RVEDVI. Further IVF administration is warranted as is serial monitoring of the patient's IAP.

PATIENT 3

Parameter	#3		#4		#5
CI	1.8		2.9		3.4
HR	160		105		88
RVEF	.25		.42		.40
RVEDVI	49	Exp Lap →	108	IVF →	130
PAOP	30		16		22
IAP	35		14		13
PIP	87		48		46
UOP	0		50		45

The patient responds appropriately to the additional IVF. He demonstrates evidence of good organ perfusion and his IAP remains at an acceptable level

PATIENT 4

- 56 yo female admitted to ICU with acute cholecystitis
  - PMH: unremarkable
- Blood cultures demonstrate Enterococcus faecalis
- Patient is hypotensive, oliguric, tachycardic
- Indications for PA catheter
  - Refractory shock
  - Oliguria

PATIENT 4

Parameter	#1
CI (L/min/m²)	1.3
HR (beats/min)	160
RVEF (fraction)	.42
RVEDVI (mL/m²)	38
PAOP (mmHg)	3
SVRI (dyne·sec·cm⁻⁵/m²)	4500
UOP (mL/hr)	0
SvO_2 (fraction)	.41

Q: What therapeutic changes should be implemented?

A: The patient is in severe septic shock. She is markedly hypovolemic. Immediate fluid resuscitation is warranted.

PATIENT 4

Parameter	#1		#2
CI	1.3		2.2
HR	160		120
RVEF	.42		.40
RVEDVI	38	3000 mL IVF	118
PAOP	3		15
SVRI	4500		2100
UOP	0		10
SvO_2	.41		.68

3 liters of IVF are administered with some response. Appropriate broad-spectrum antibiotics are started.

Q: What therapeutic changes should be implemented now?

A: Further fluid resuscitation is warranted as the patient's systemic perfusion remains inadequate.

PATIENT 4

Parameter	#1		#2		#3
CI	1.3		2.2		2.3
HR	160		120		110
RVEF	.42		.40		.30
RVEDVI	38	IVF	118	IVF	150
PAOP	3		15		17
SVRI	4500		2100		1900
UOP	0		10		22
SvO_2	.41		.68		.67

Additional IVF is given with a decrease in RVEF and rise in RVEDVI. CI and UOP remain low and SVRI is dropping. You recognize that increased contractility and afterload is needed.

Q: What therapeutic changes should be implemented now?

A: You initiate a norepinephrine infusion to raise the patient's afterload and improve contractility.

PATIENT 4

Parameter	#3		#4		#5
CI	2.3		0.9		2.6
HR	110		110		130
RVEF	.30		.13		0.22
RVEDVI	150	NE	220	NE IVF	170
PAOP	17		26		22
SVRI	1900		540		1100
UOP	22		0		25
SvO_2	.67		.44		.62

The patient develops severe septic shock, but with time, additional IVF, norepinephrine, and antibiotics, her shock state improves.

CONCLUSIONS

- Volumetric pulmonary artery catheter monitoring is a valuable tool in the care of the critically ill
- RVEDVI is superior to PAOP and CVP in predicting response to resuscitation
- RVEDVI must be interpreted in conjunction with the RVEF
- Continuous hemodynamic monitoring provides time critical information that is useful for guiding resuscitation

CONTINUOUS CO MONITORING

- Continuously updated
  - Preload (RVEDVI)
  - Contractility (CI)
  - RV afterload (RVEF)
  - Oxygen transport balance (SvO_2)

- Provides a comprehensive assessment of cardiopulmonary function