Understanding The Maths Behind PiCCO™

Measurements

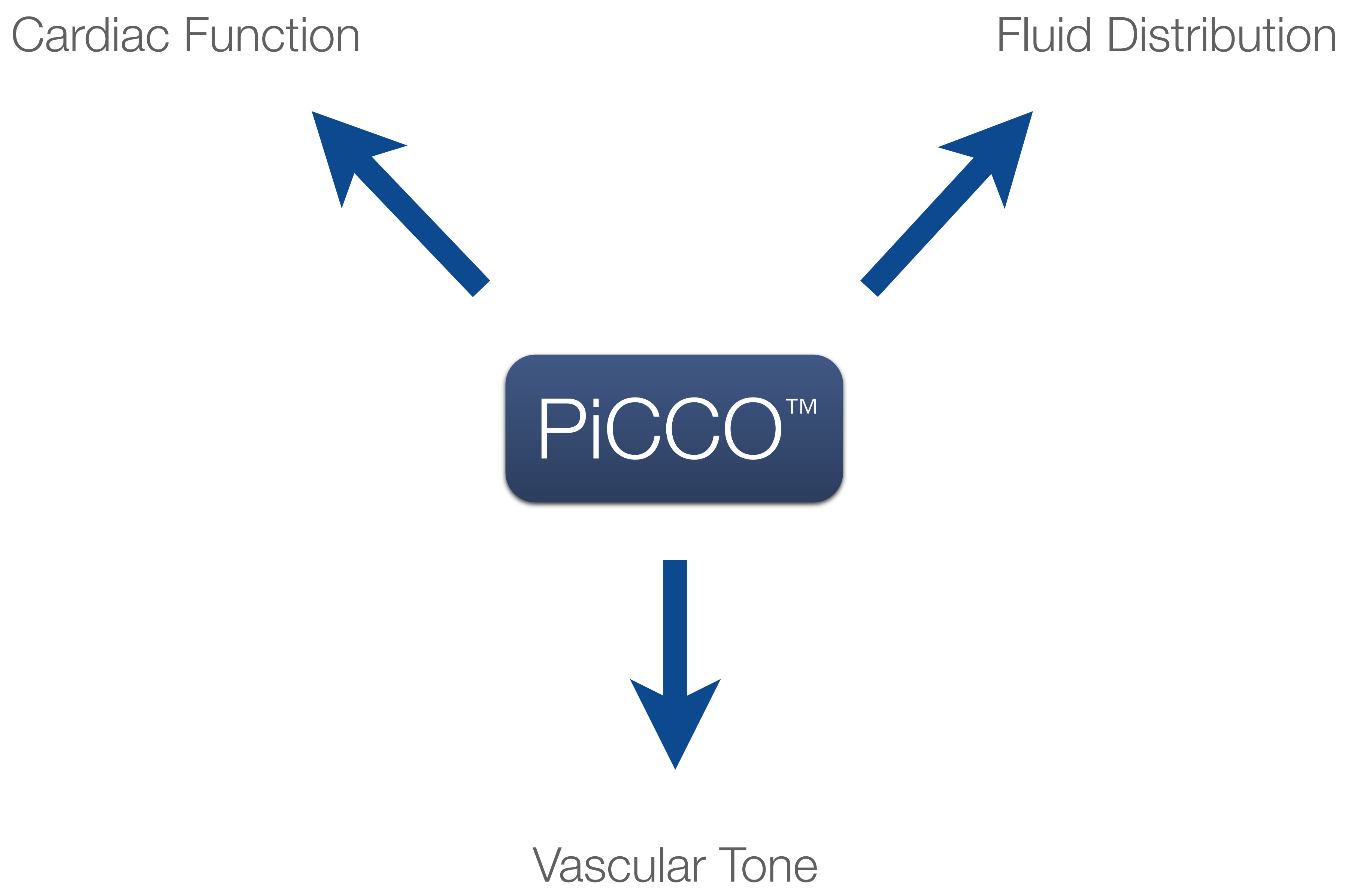
- Blood pressure
- Arterial blood temperature
- Time
- Injectate (volume) and temperature

- Patient height, sex and age

Derived values

- Heart rate
- Cardiac output
- Stroke volume
- Stroke volume variation
- Pulse pressure variation
- Global end diastolic volume
- Intrathoracic blood volume
- Extravascular lung water
- Systemic vascular resistance

- Cardiac index
- Cardiac function index
- Global end diastolic volume index
- Intrathoracic blood volume index
- Extravascular lung water index
- Systemic vascular resistance index

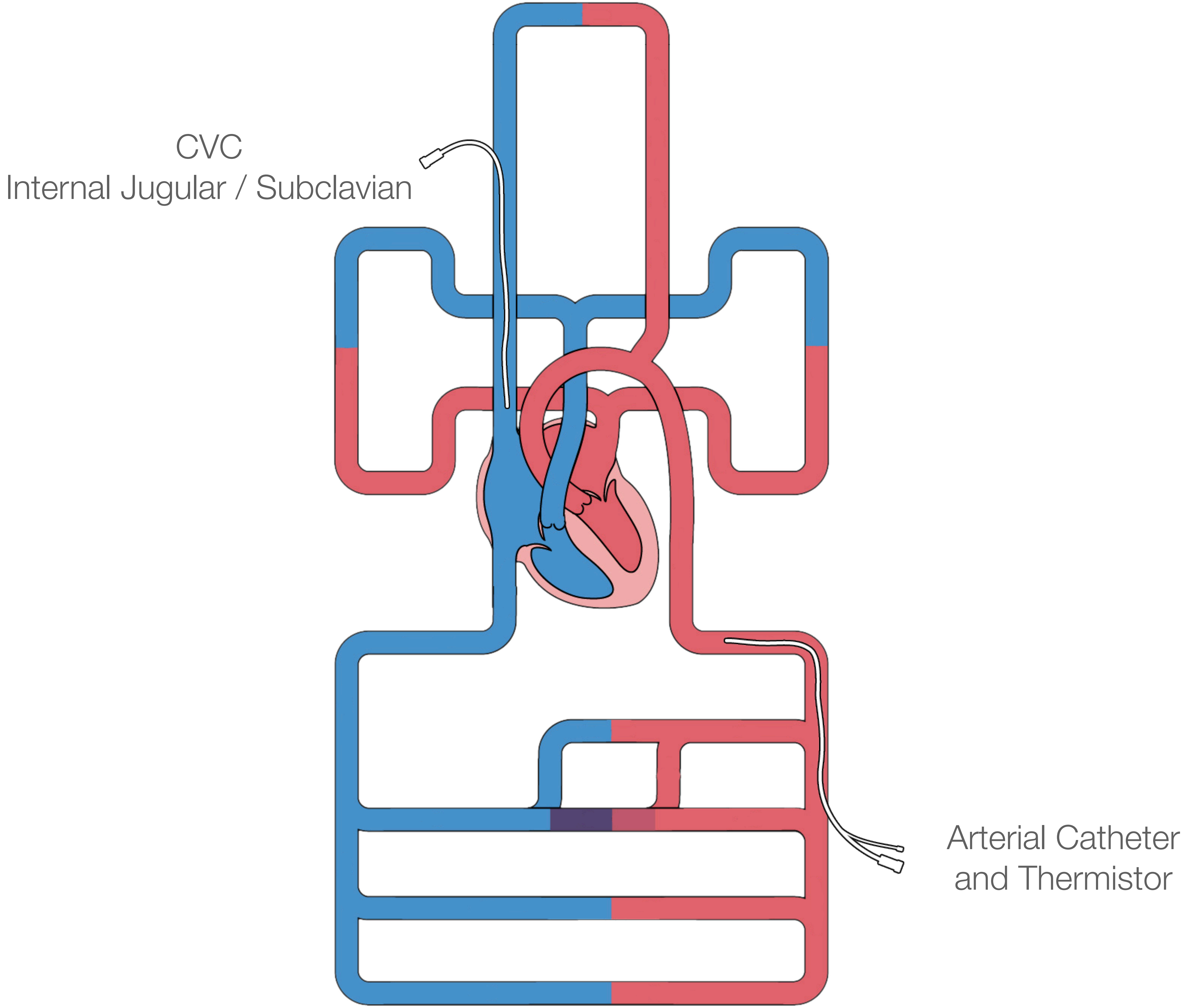

Cardiac Function
Fluid Distribution
PiCCO™
Vascular Tone

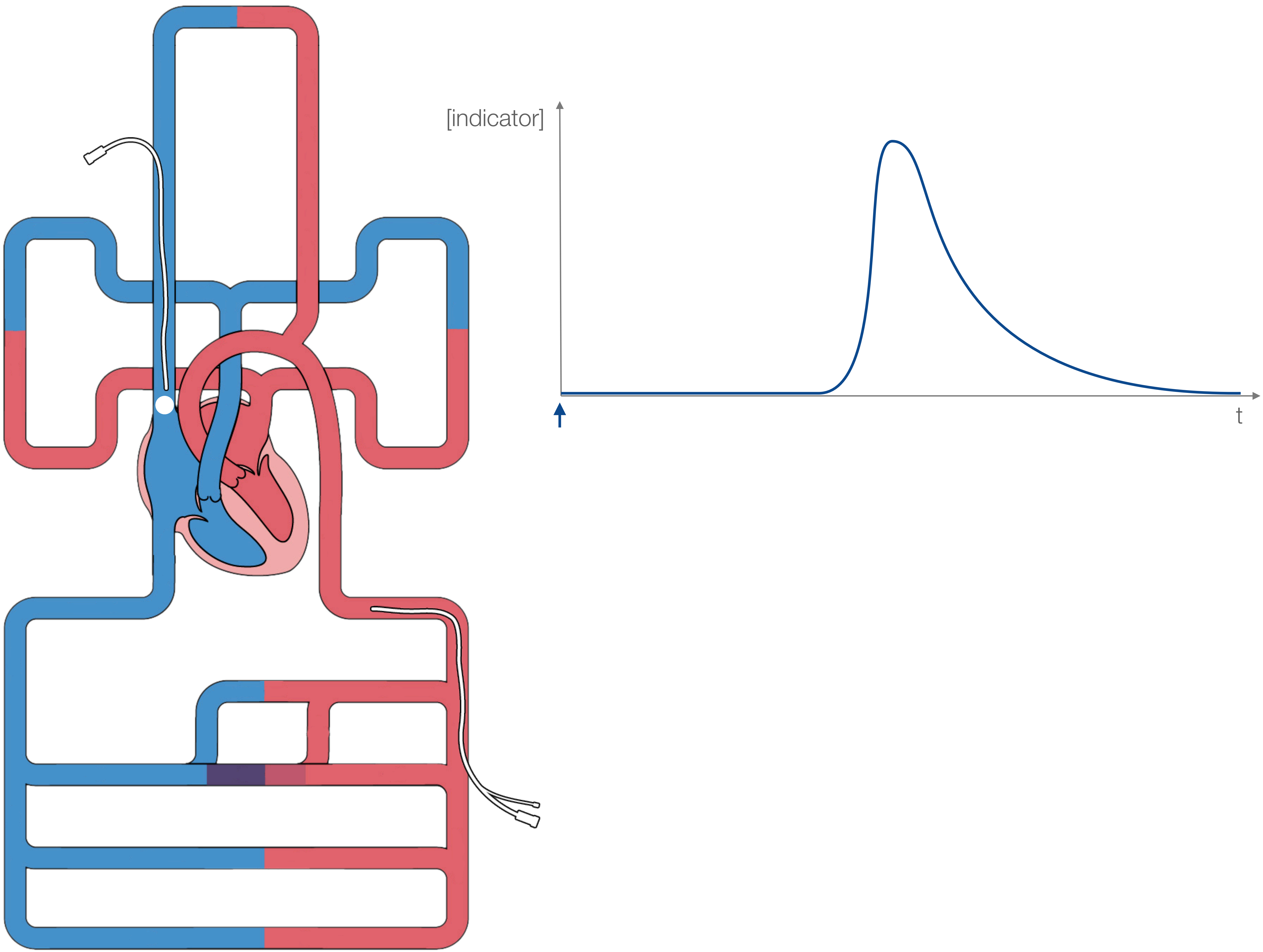

Thermodilution
PiCCO™
Pulse Contour

The Maths Behind PiCCO™

- Cardiac Function
- PiCCO in Action
- Fluid Distribution
- Vascular Tone
- Calibrated Pulse Contour Analysis

Cardiac Function


CVC
Internal Jugular / Subclavian
Arterial Catheter
and Thermistor

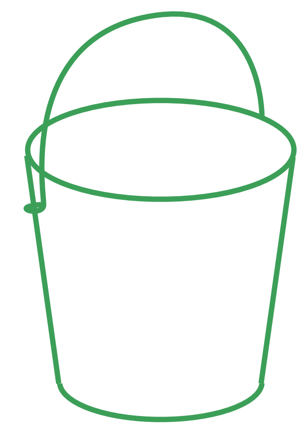


[indicator]
t

Stewart-Hamilton

$$Flow = \frac{Volume}{Time}$$

$$Volume = \frac{Amount\ of\ Indicator}{\Delta\ Concentration}$$



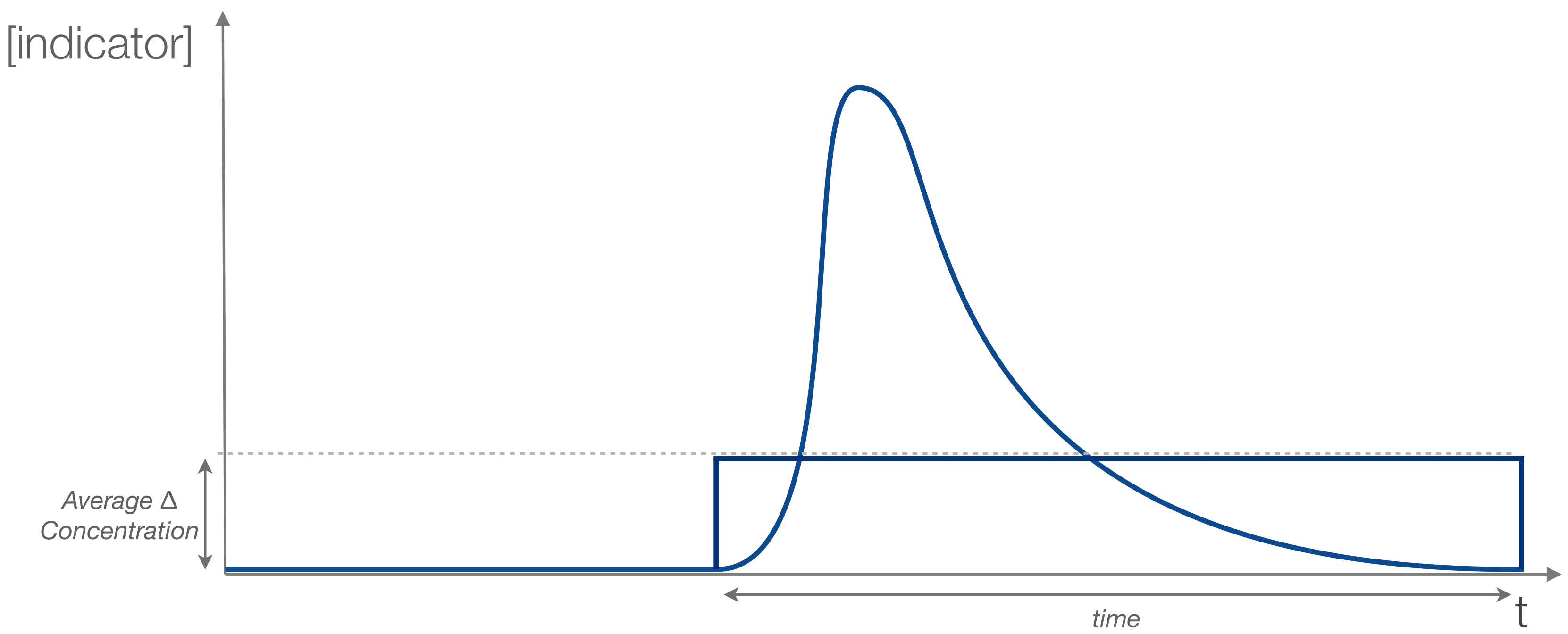
Bucket full of pure water

5mg of indicator

Indicator concentration after mixing is 2.5mg/l

What is the volume of water in the bucket?

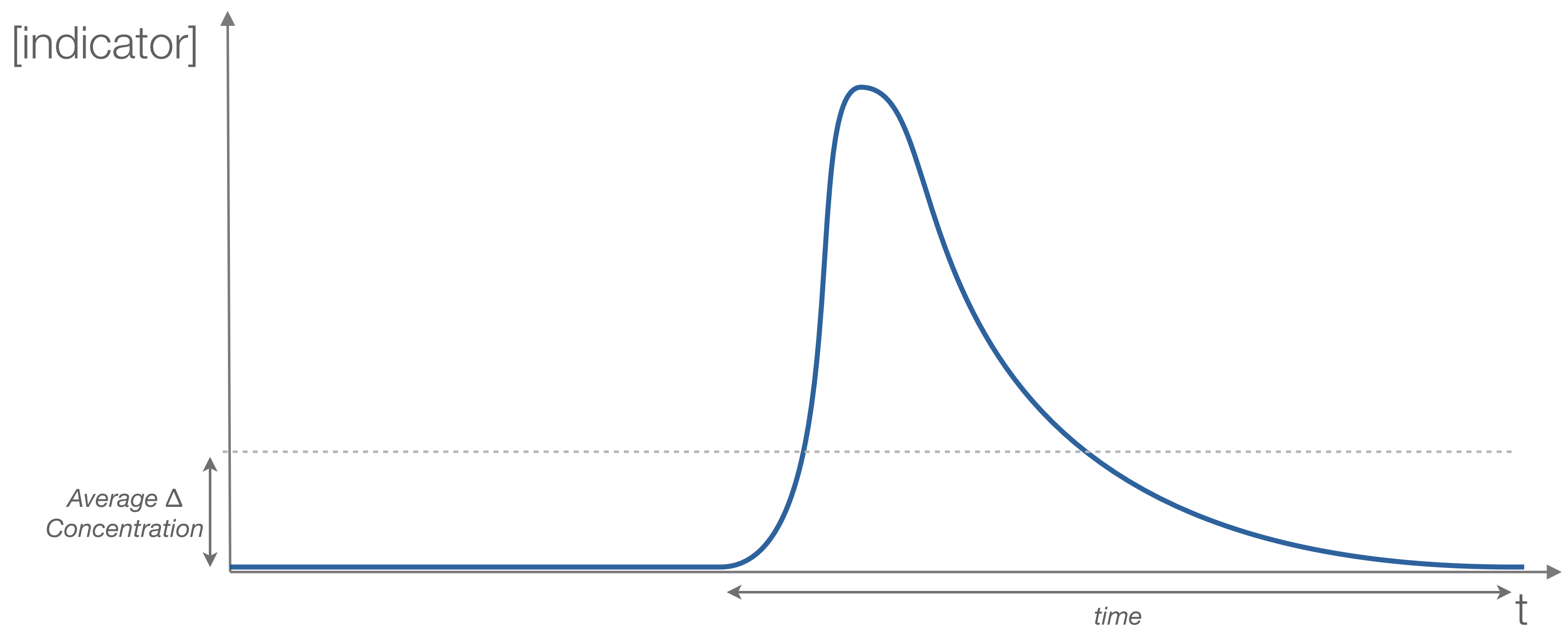
Stewart-Hamilton



$$\text{Volume} = \frac{\text{Amount of Indicator}}{\text{Average } \Delta \text{ Concentration}}$$

$$\text{Cardiac Output} = \frac{\left(\dfrac{\text{Amount of Indicator}}{\text{Average } \Delta \text{ Concentration}}\right)}{\text{time}}$$

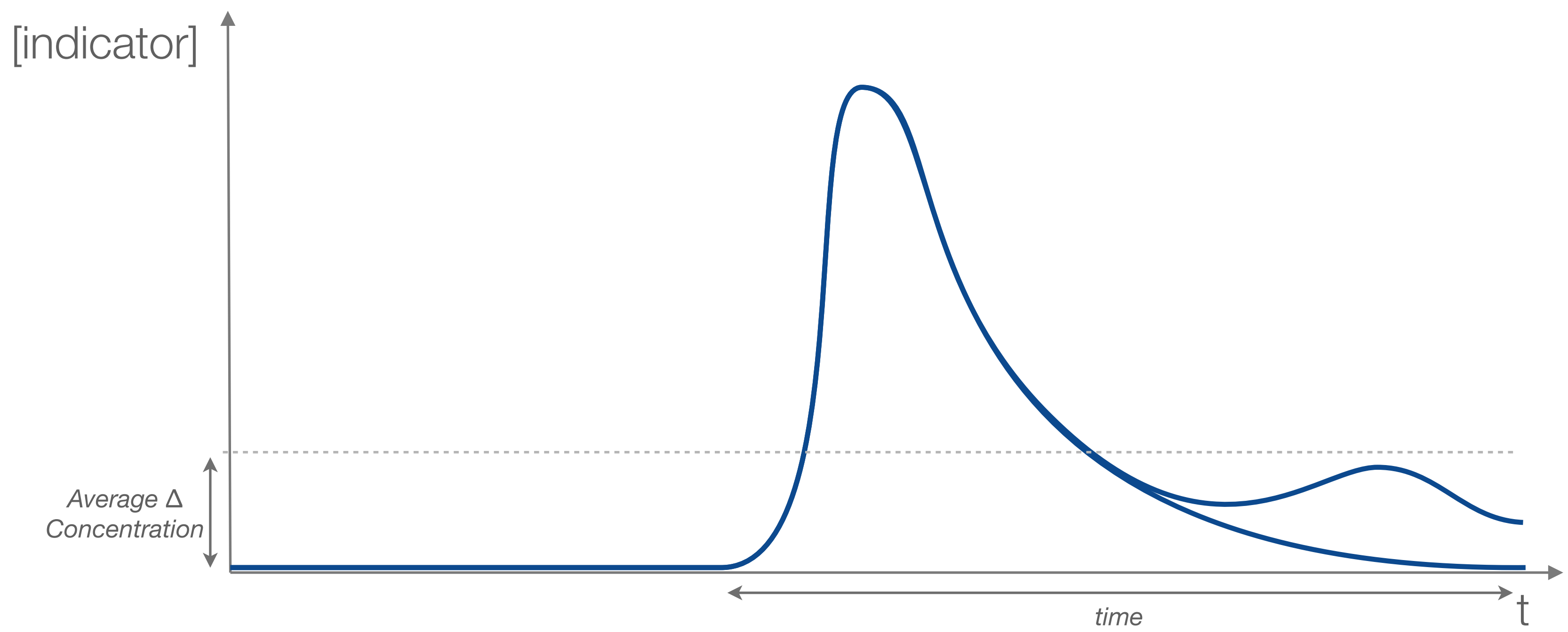
Stewart-Hamilton



$$Volume = \frac{Amount\ of\ Indicator}{Average\ \Delta\ Concentration}$$

$$Cardiac\ Output = \frac{Amount\ of\ Indicator}{Average\ \Delta\ Concentration\ .\ time}$$

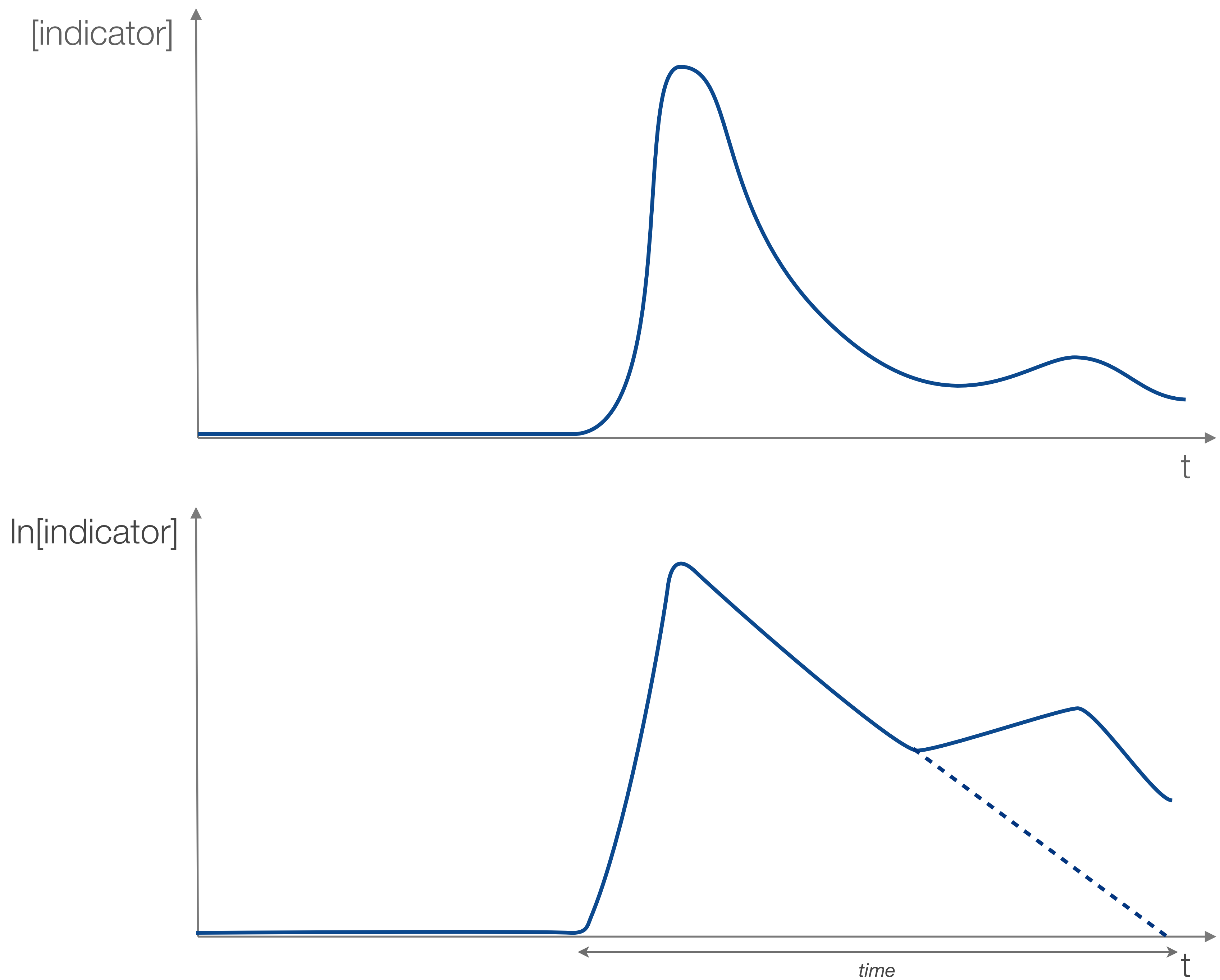
Recirculation



$$Volume = \frac{Amount\ of\ Indicator}{Average\ \Delta\ Concentration}$$

$$Cardiac\ Output = \frac{Amount\ of\ Indicator}{Average\ \Delta\ Concentration\ .\ time}$$

Correcting for Recirculation



PiCCO Thermodilution

$$Cardiac\ Output = \frac{V\ (T_b - T_i)\ K_1\ K_2}{\int_0^{\infty} \Delta T_b\ .\ \Delta t}$$

where:

V is volume of injectate

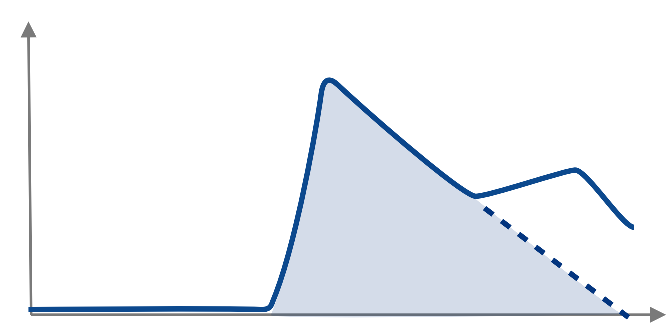
T_b is initial blood temperature

T_i is injectate temperature

K_1 corrects for specific gravity of blood

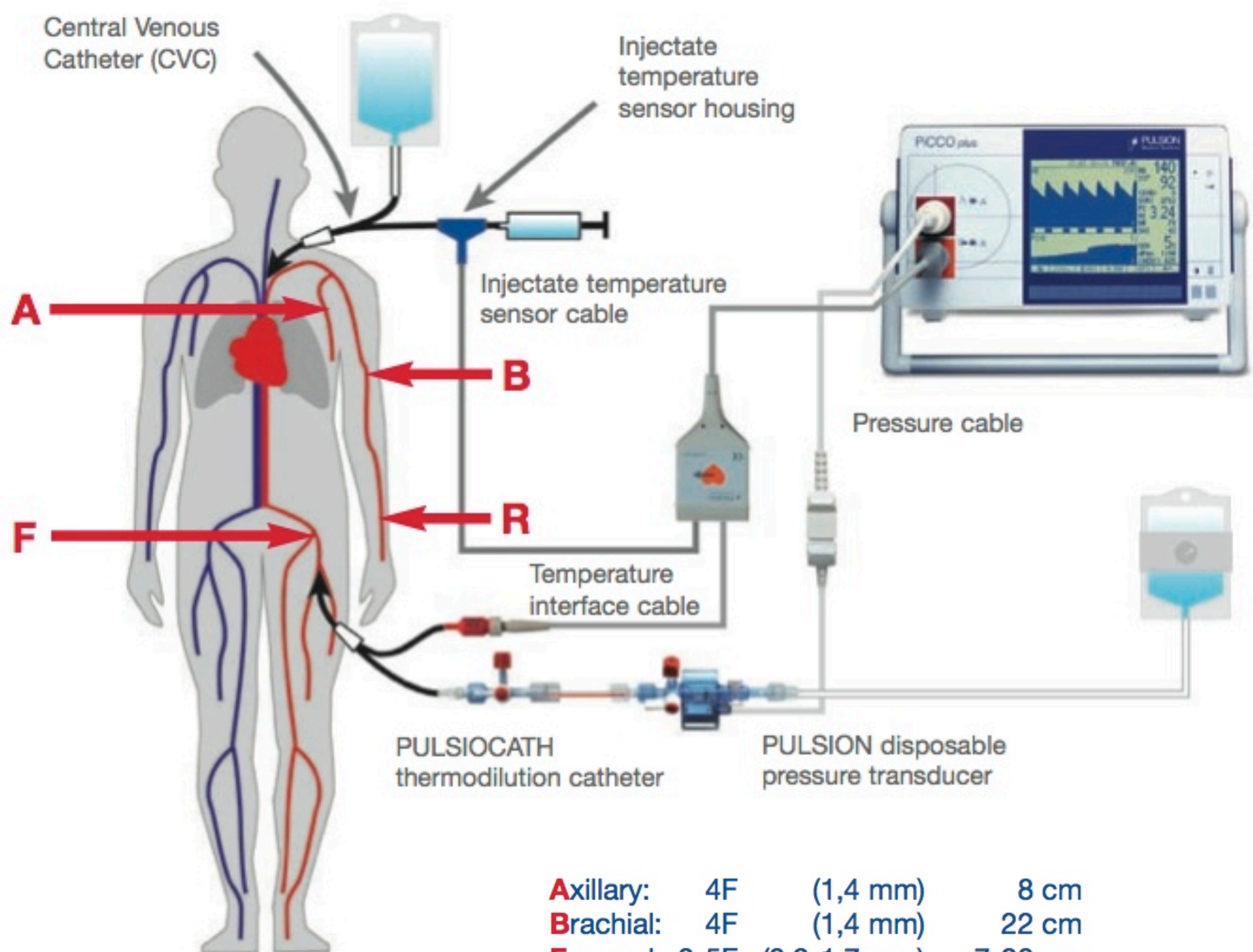
K_2 corrects for units, catheter dead space and rate of heat change

t is time



PiCCO™ in action

PiCCO™ Plumbing



Axillary:	4F	(1,4 mm)	8 cm
Brachial:	4F	(1,4 mm)	22 cm
Femoral:	3-5F	(0,9-1,7 mm)	7-20 cm
Radial:	4F	(1,4 mm)	50 cm

PiCCO Arterial Lines (Pulsocath™)

PV2015L20
Femoral artery in adults
Ø 5F, length 20 cm

The most commonly used PiCCO Catheter for use in the femoral artery of adults. It is proven that catheters positioned in the femoral artery are not associated with a higher rate of catheter-related complications than radial artery catheters. [1]

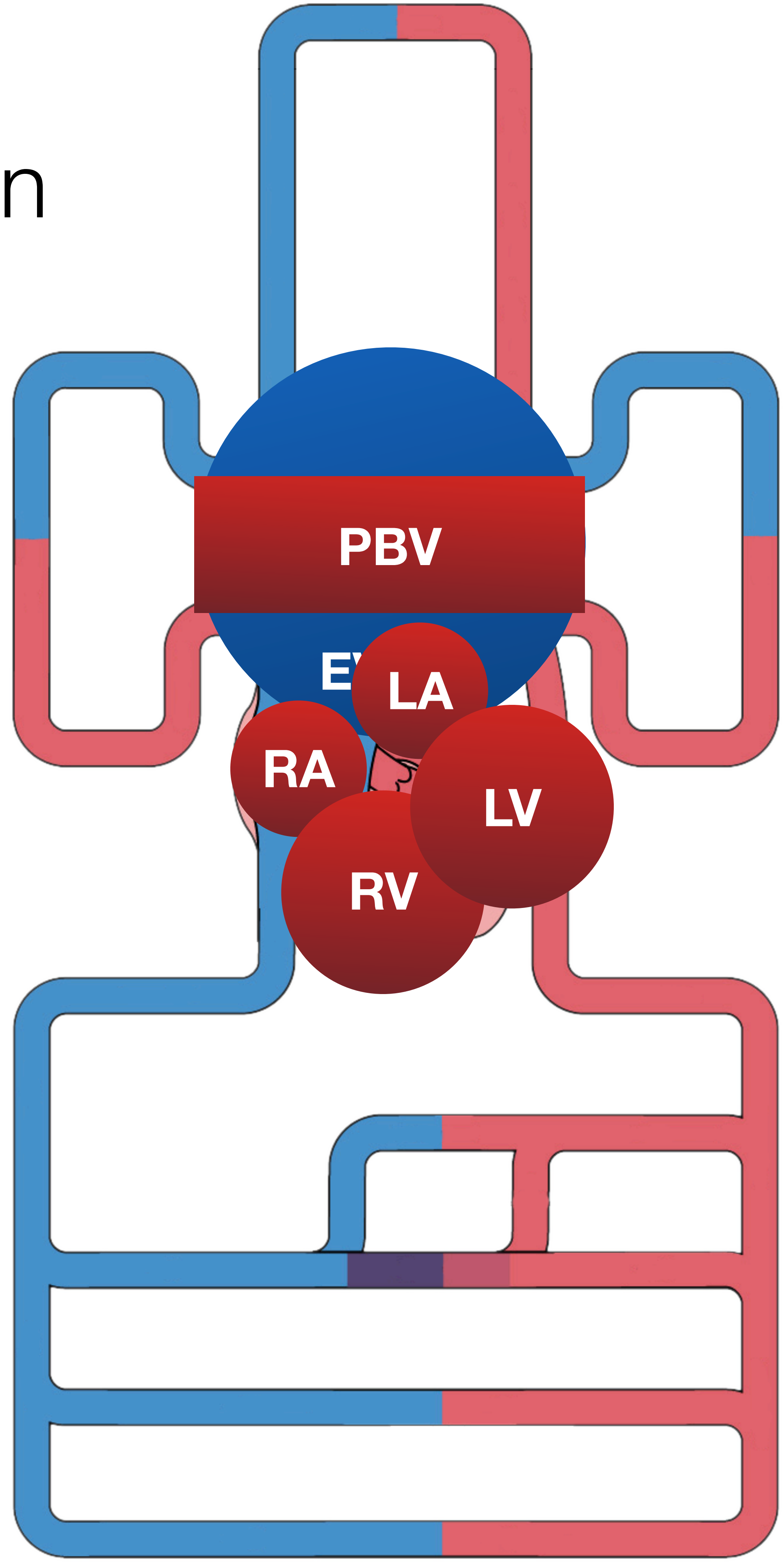
PV2014L22
Brachial artery in adults
Ø 4F, length 22 cm

On account of the longer length, but smaller diameter, this model is particularly suitable for use in the brachial artery of adults.
The brachial artery should be punctured so that the tip of the catheter reaches the axillary artery. [2]

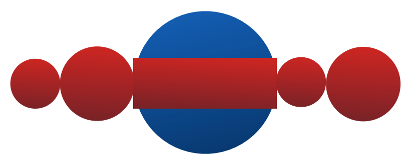
PiCCO™ Thermodilution in action

Fluid Distribution

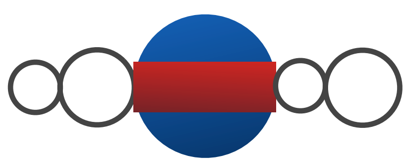
Fluid Distribution



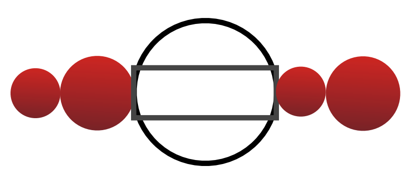
Accessible Compartments: PiCCO™



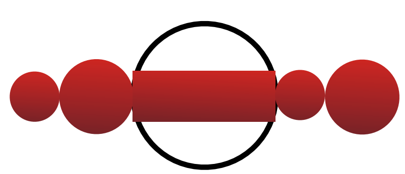
Intrathoracic Thermal Volume



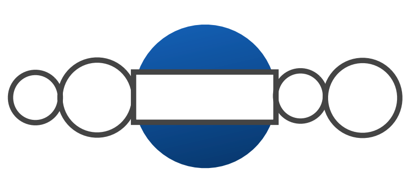
Pulmonary Thermal Volume



Global End Diastolic Volume



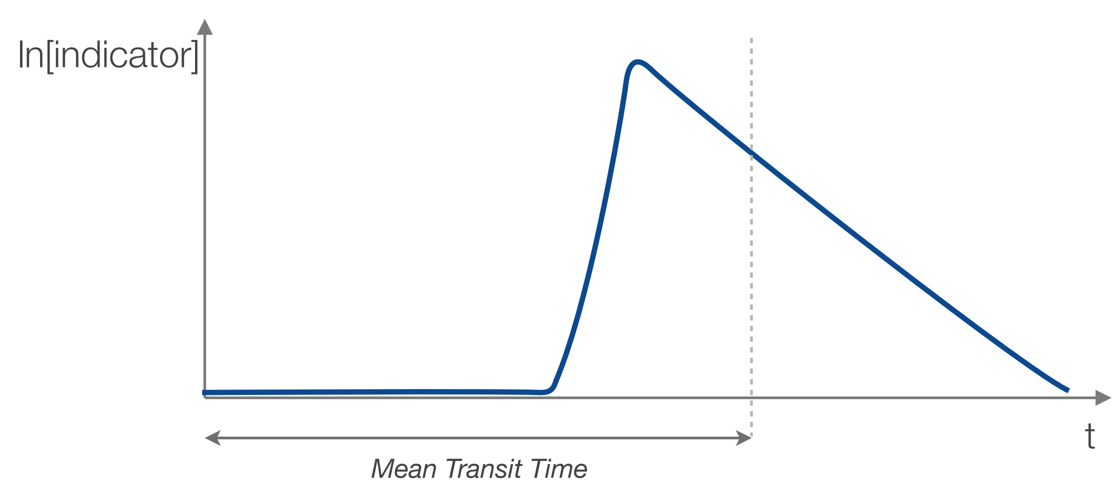
Intrathoracic Blood Volume



Extravascular Lung Water

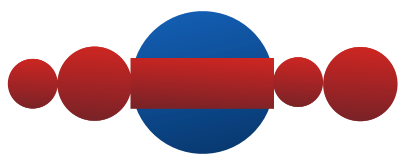
Intrathoracic Thermal Volume

- Water conducts heat rapidly
- Thermal indicator distributes rapidly to all interstitial and intracellular compartments within a few micrometers of the pulmonary vascular tree



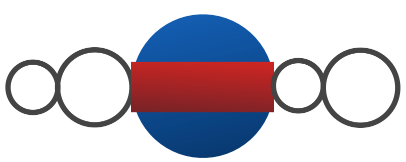
Intrathoracic Thermal Volume = Cardiac Output . Mean Transit Time

Accessible Compartments: PiCCO™

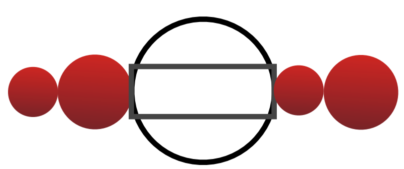


Intrathoracic Thermal Volume

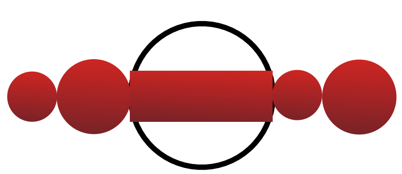
$$ITTV = CO \cdot MTT$$



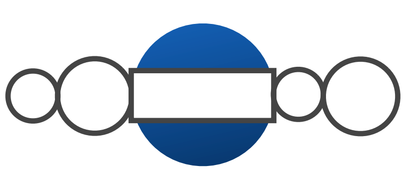
Pulmonary Thermal Volume



Global End Diastolic Volume



Intrathoracic Blood Volume



Extravascular Lung Water

The Dye Dilution Method for Describing the Central Circulation

An Analysis of Factors Shaping the Time-Concentration Curves

By Elliot V. Newman, M.D., Margaret Merrell, Sc.D., Abraham Genecin, M.D., Carlos Monge, M.D., William R. Milnor, M.D., and William P. McKeever, M.D.

In addition to providing accurate measurement of circulation times and cardiac output, the dye dilution curves may reveal the size and location of the volumes of blood with which the dye is mixed in the central circulatory system. A trivalent approach to the analysis of these curves is presented by a combination of theoretic analysis, mechanical system experimentation and clinical observation.

THE method for measuring cardiac output based on the "dye dilution" principle of Stewart and Hamilton[1, 2] involves the injection of a known amount of colored substance into a vein and collection of serial samples of blood from an artery for determination of the concentration of dye. Other substances have been used for injection, such as salt solution and radioactive cells.[3, 4]

The validity of this method of measurement of flow depends on the assumption that the dye is distributed throughout a "central" pool of blood as it passes from the vein into the right heart chambers, the lungs, the left heart and out into the arterial system of vessels. The validity and accuracy of the method for determining rates of flow in mechanical systems and the cardiac output in animals and human subjects have been determined by other workers.[5, 6]

Our interest in the dye dilution curves has been in the theoretic and possible practical information to be derived from the shape of the curves. It was pointed out by Hamilton and others that the shape of these curves is governed not only by the flow, but also by the volume of blood in the central pool in which the dye is distributed. Previous analyses of these curves have tended to neglect the possibility that the anatomic characteristics of the pool might affect the shape of the curve, although it is obvious that, in the living organism, the central pool in which the dye is distributed is not a single volume, but a *series* of volumes made up of the veins through which the dye reaches the heart, the right heart chambers, the lung vessels, and the left heart chambers.[4, 6, 7]

The purposes of our studies are (1) to derive a theory which will describe the dye concentration change in the outflow of systems made up of series of volumes or chambers, (2) to test the theory by comparison with dilution curves obtained from mechanical models in which the flow and volumes are known and (3) to apply the theory to the dilution curves obtained on human subjects.

In setting up theoretic and mechanical systems we have started with the simplest case and proceeded to more complex models as the differences between human curves and theoretic curves suggested lines on which the assump-

---

From the Department of Medicine of the Johns Hopkins University School of Medicine and Hospital and the Department of Biostatistics of the School of Hygiene and Public Health (Paper No. 269), Baltimore, Md.

This study was supported by a Grant from the Life Insurance Medical Research Fund.

During the course of the research, W. R. M. was a Postgraduate Research Fellow of the National Institutes of Health; C. M. was a Rockefeller Fellow in Medicine; A. G. was a Research Fellow of the American Heart Association, 1949–1950.

Pulmonary Thermal Volume

Newman's Indicator Dilution Theory

Newman E, Merrell M, Genecin A, Monge C, Milnor WR, and McKeever WP. *Circulation* 4: 735–746, 1951.

The fluid compartments of the thorax are mixing chambers connected in series.

The pulmonary thermal volume behaves as a single mixing chamber for thermal indicator.

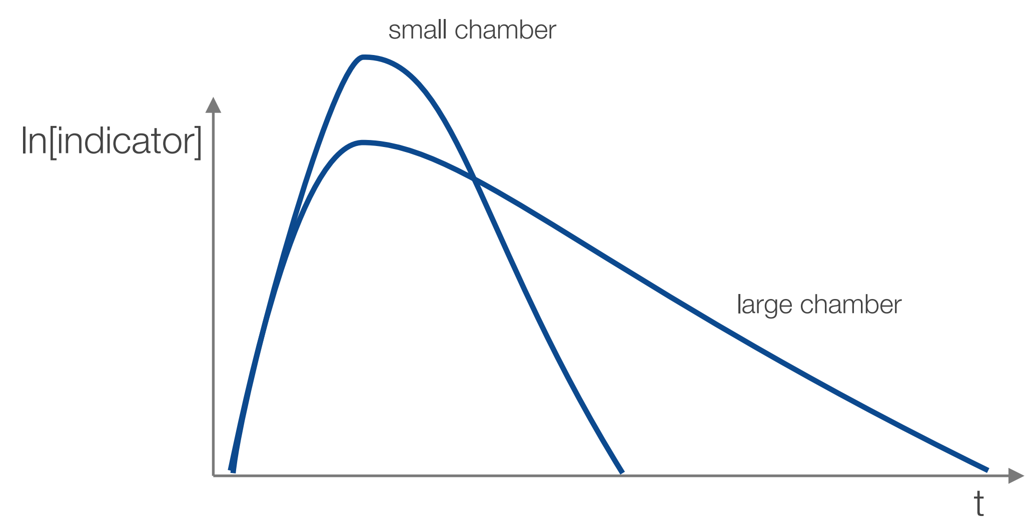
The pulmonary thermal volume is the largest chamber.

rate of change of indicator

$$\frac{dA}{dt} = -\frac{QA}{V}$$

after integration

$$c = \frac{A}{V} e^{-\left(\frac{Q}{V}\right)}$$



The washout curve of indicator at the end of the series is dominated by the washout of the largest chamber.

Pulmonary Thermal Volume

In an exponential decay:

$$N_{(t)} = N_0 \cdot e^{\left(\frac{-t}{\tau}\right)}$$

where:

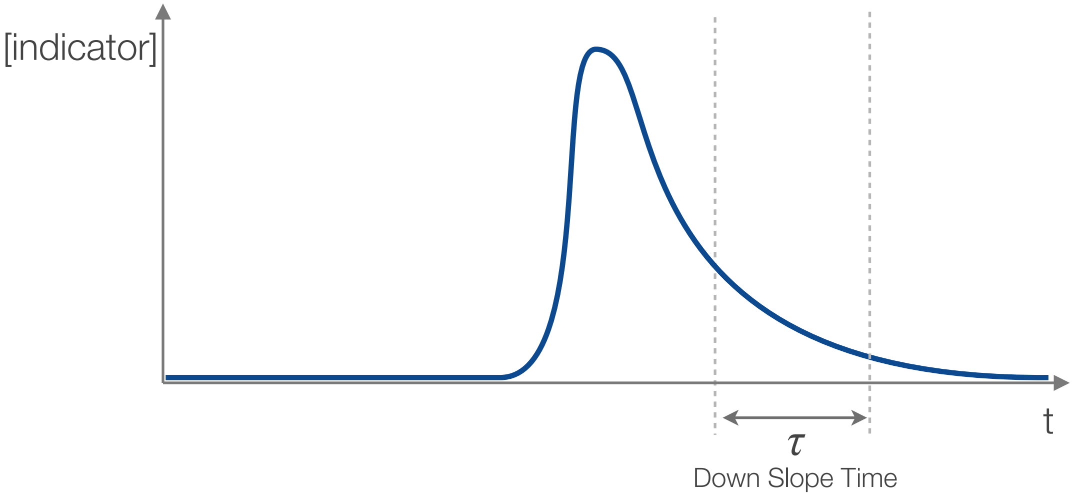
τ is the time constant

$$t_{(\frac{1}{2})} = \ln 2 \cdot \tau$$

or:

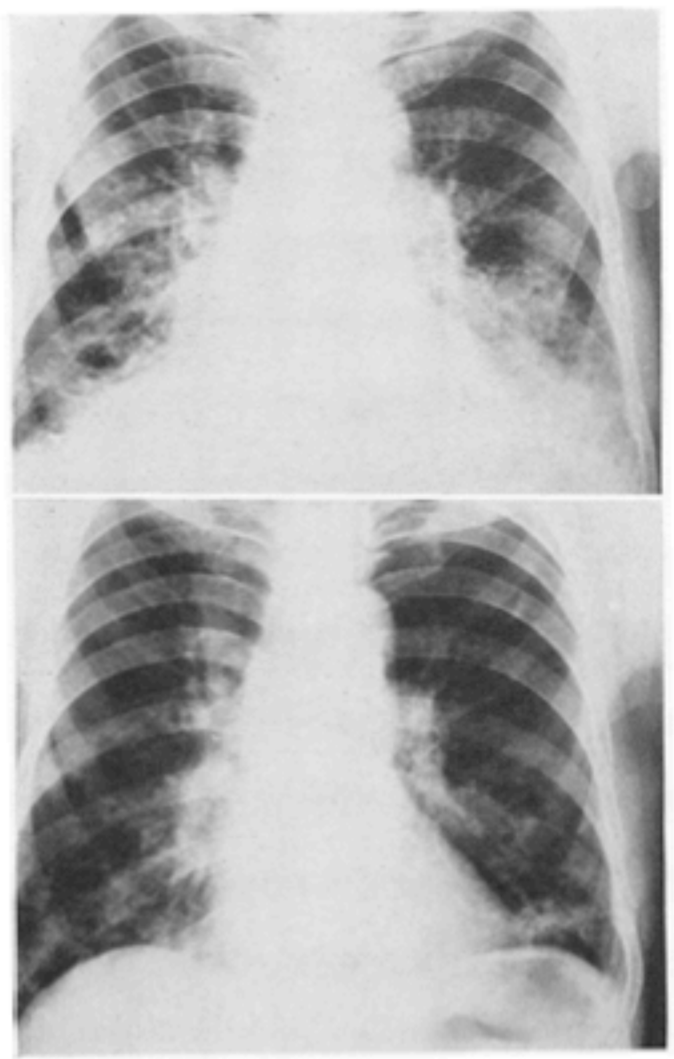
$$\tau = \frac{\ln 2}{t_{(\frac{1}{2})}}$$

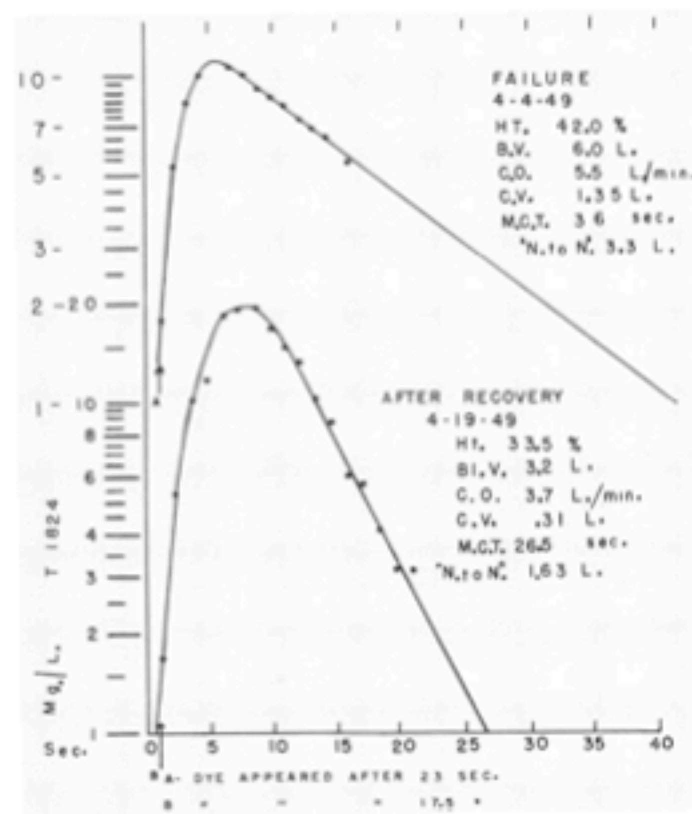
Polonium-210 has a half-life of 138 days, and a time constant of 200 days



$$\textit{Pulmonary Thermal Volume} = \textit{Cardiac Output} \cdot DSt$$

Newman’s Clinical Data





Journal of
APPLIED
PHYSIOLOGY

VOLUME 6 — *June 1954* — NUMBER 12

On the Theory of the Indicator-Dilution Method for Measurement of Blood Flow and Volume[1]

PAUL MEIER AND KENNETH L. ZIERLER. *From the Departments of Biostatistics,*[2] *Environmental Medicine, and Medicine, The Johns Hopkins University, Baltimore, Maryland*

ABOUT 60 YEARS AGO Stewart (1) introduced and for the past 25 years Hamilton and his colleagues (2) have developed and extended the indicator-dilution technics for measurement of cardiac output. These methods have more recently been applied to measurement of regional blood flow. Although there has been some criticism of the use of the indicator-dilution technics to measure blood *flow*, its application for this purpose has achieved wide acceptance.

It was also Stewart (3) who first used these technics to measure the *volume* of blood in the heart and lungs, and again it was Hamilton and his colleagues (2) who developed and emphasized the use of mean circulation time to determine the volume of a vascular bed. It is of interest that mean circulation time has also been applied in hydraulic engineering to the measurement of the volume of water conduits (4). No theory was presented and the mean time was only one of several parameters used.

This application of the Stewart-Hamilton methods has been subject to considerable controversy and misinterpretation. The mean time has on occasion been confused with the median time, and several workers have expressed doubt as to the validity or meaning of the measurement of volume as a function of the mean circulation time (5, 6).

The basic relationship, volume = flow times mean circulation time, has been accepted as obvious by proponents of these methods. However, in view of the confusion which has arisen it may be of some value to present a direct proof of its validity under appropriate conditions.

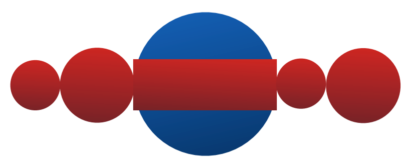
It is the purpose of this paper to present such a proof, and also to consider the

Received for publication March 15, 1954.

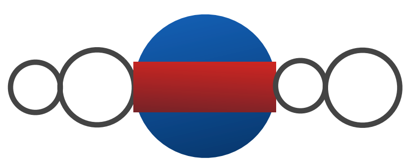
[1] These studies were aided by contracts between the Office of Naval Research, Department of the Navy, and The Johns Hopkins University, [NR 113-241 and Nonr-284(16)] and a grant (H-1327) from the National Institutes of Health, Department of Health, Education, and Welfare.

[2] Paper No. 293.

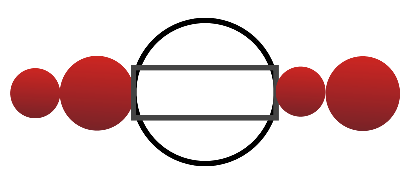
Accessible Compartments: PiCCO™



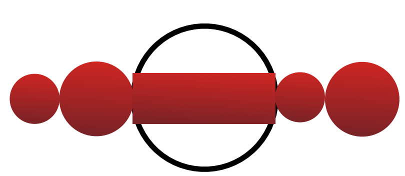
Intrathoracic Thermal Volume $ITTV = CO \cdot MTT$



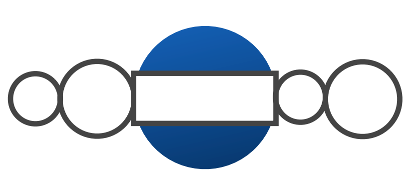
Pulmonary Thermal Volume $PTV = CO \cdot DSt$



Global End Diastolic Volume $GEDV = ITTV - PTV$

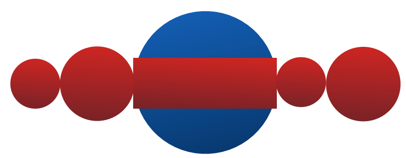


Intrathoracic Blood Volume



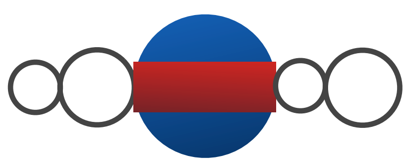
Extravascular Lung Water

Double Indicator Dilution Technique



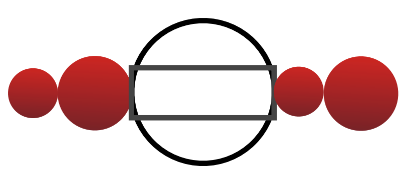
Intrathoracic Thermal Volume

$ITTV = CO \, . \, MTT$



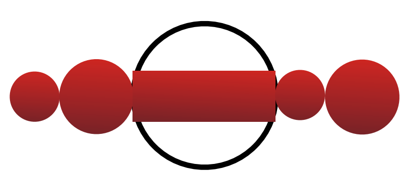
Pulmonary Thermal Volume

$PTV = CO \, . \, DSt$



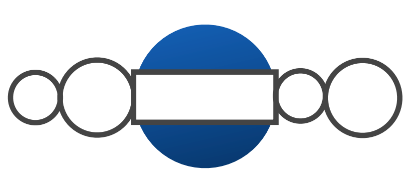
Global End Diastolic Volume

$GEDV = ITTV - PTV$



Intrathoracic Blood Volume

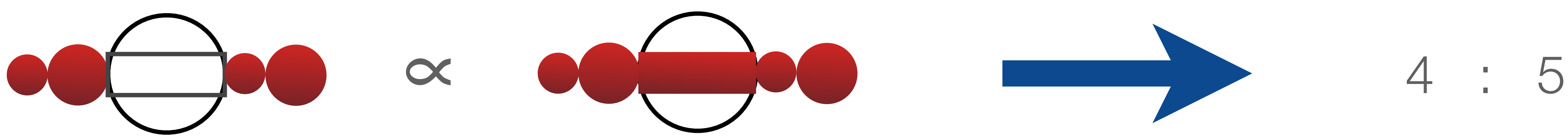
Volume of distribution of iodocyanine green



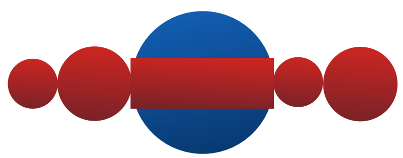
Extravascular Lung Water

Intrathoracic Blood Volume

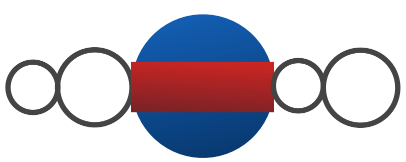
Sakka SG, Ruhl CC et al. **Assesment of cardiac preload and extravascular lung water by single transpulmonary thermodilution.** *CIntensive Care Med* 2000; 26:180-187



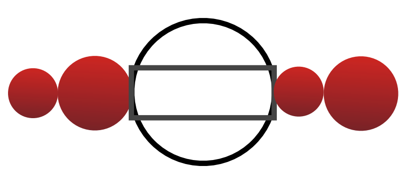
Accessible Compartments: PiCCO™



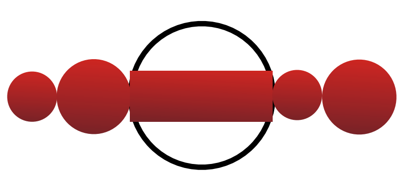
Intrathoracic Thermal Volume — $ITTV = CO . MTT$



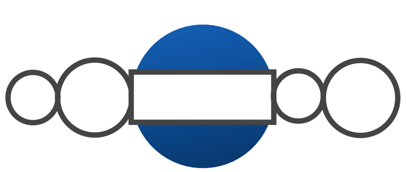
Pulmonary Thermal Volume — $PTV = CO . DSt$



Global End Diastolic Volume — $GEDV = ITTV - PTV$



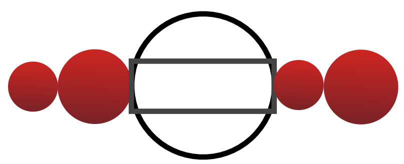
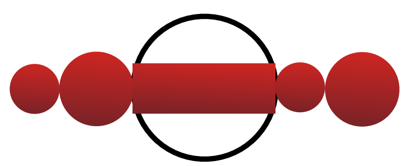
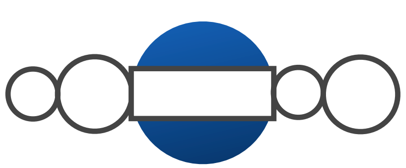
Intrathoracic Blood Volume — $ITBV = 1.25\ ITTV$



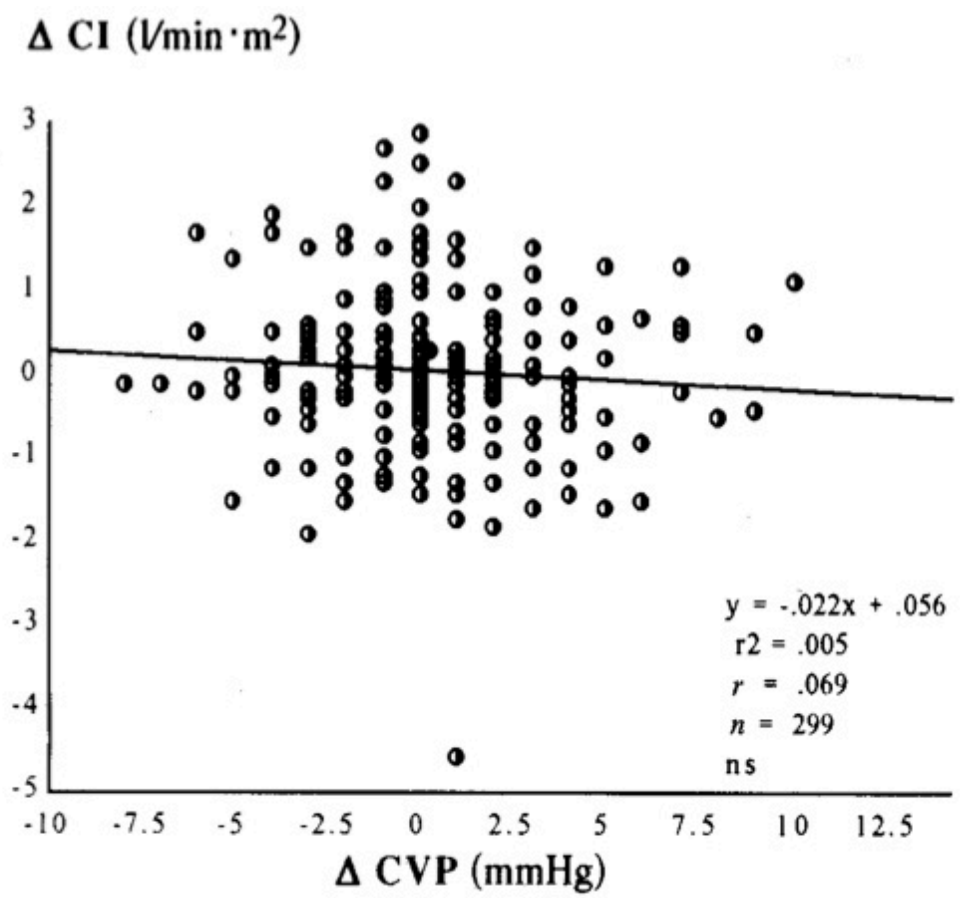
Extravascular Lung Water — $EVLW = ITTV - PTV$

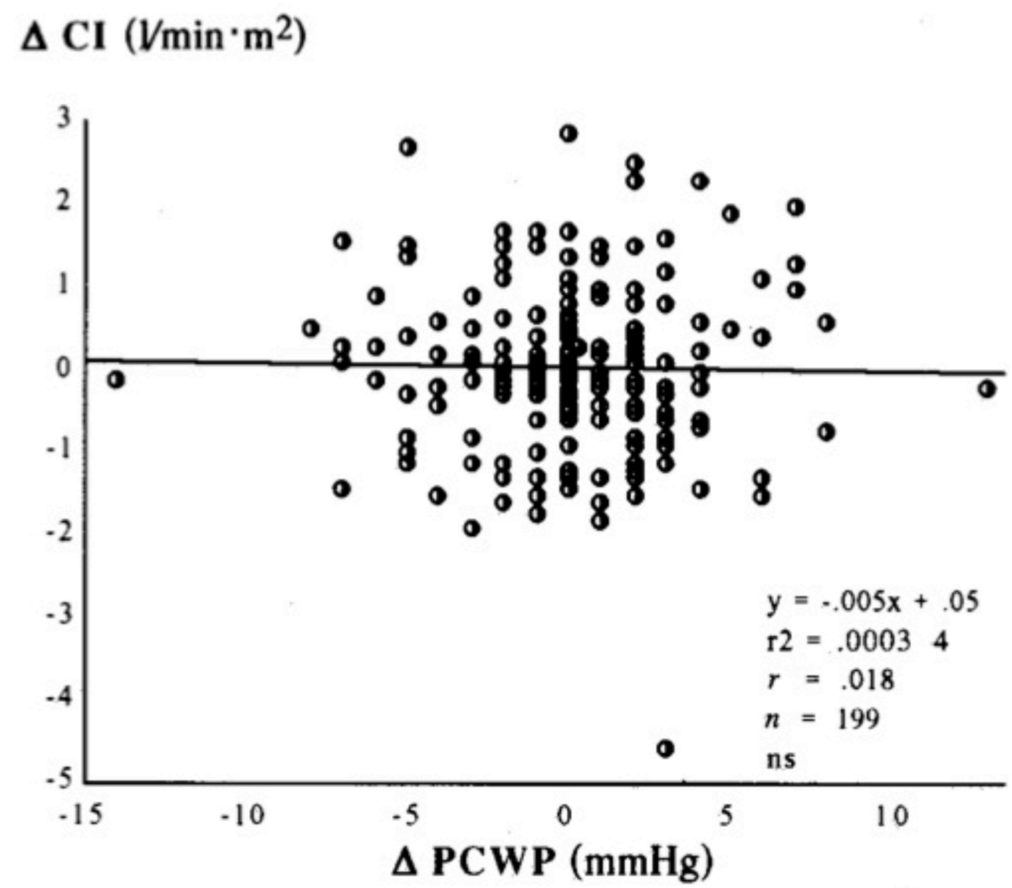
Indexed Values

- Predicted body weight / surface area provides more accurate results, particularly in overweight patients.
- Predicted values based on age, sex, and height

	GEDVI	Predicted Weight	$ml.m^{-2}$
	ITBVI	Predicted Weight	$ml.m^{-2}$
	EVLWI	Predicted Surface Area	$ml.kg^{-2}$

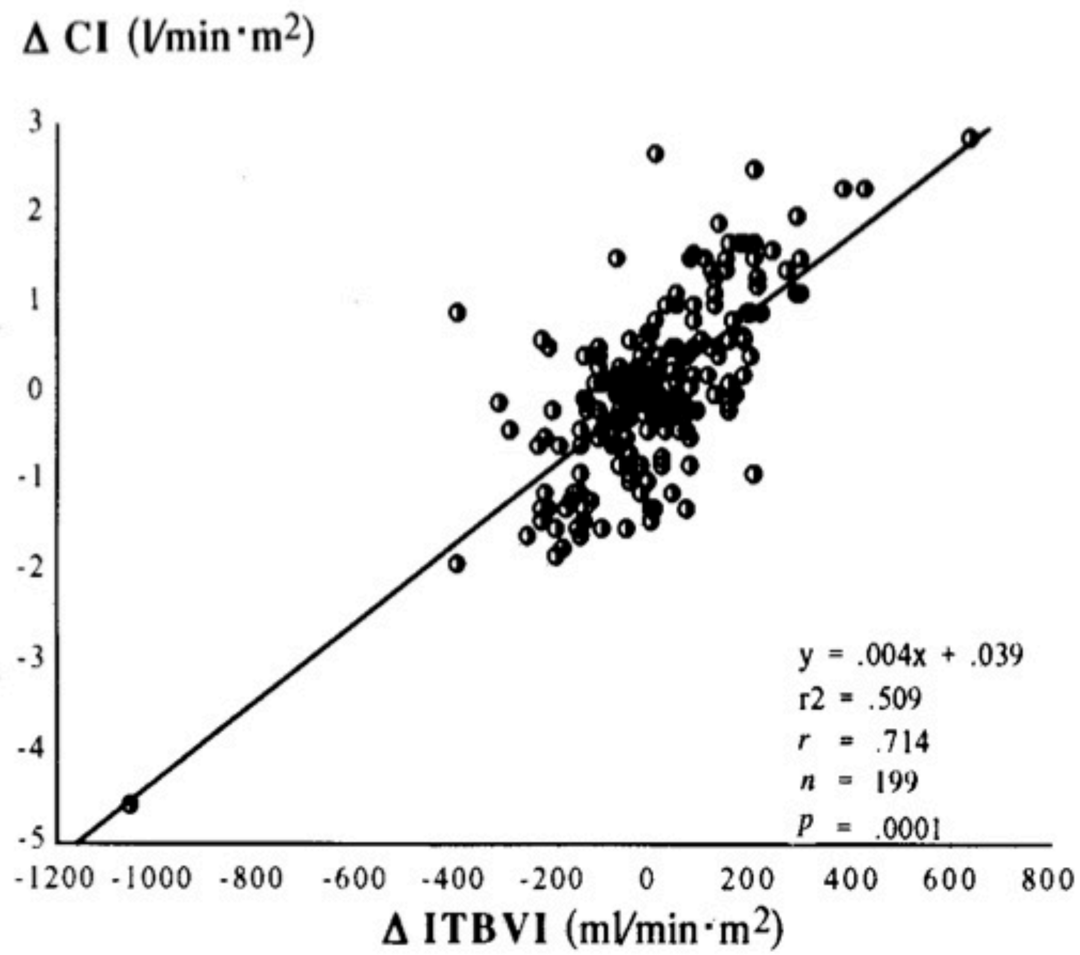
Pressure as an Indicator of Preload





Lichtwarck-Aschoff M. et al,**Intrathoracic blood volume accurately reflects circulatory volume status in critically ill patients with mechanical ventilation.** *Intensive Care Medicine* 18: 142-147, 1992

Volume as an Indicator of Preload



Lichtwarck-Aschoff M. et al, **Intrathoracic blood volume accurately reflects circulatory volume status in critically ill patients with mechanical ventilation.** *Intensive Care Medicine* 18: 142-147, 1992

Cardiac Function Index

$$\textit{Cardiac Function Index} = \frac{\textit{Cardiac Index}}{\textit{Global End Diastolic Volume Index}}$$

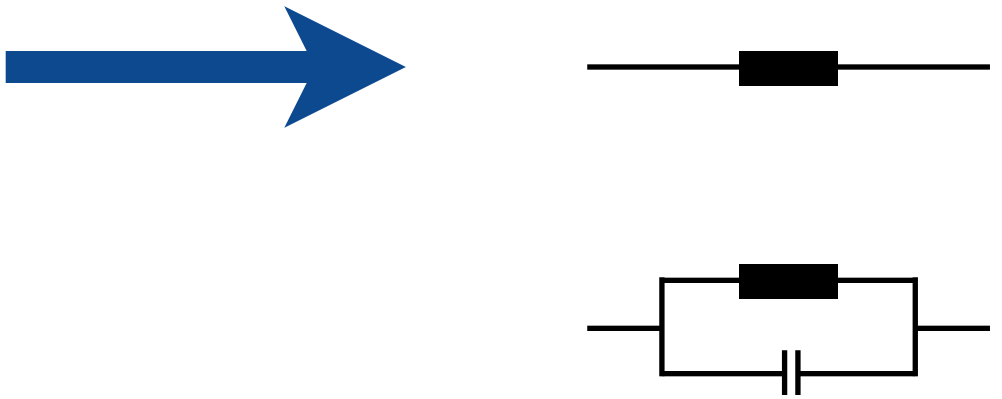
- Independent of preload
- Inotrope titration

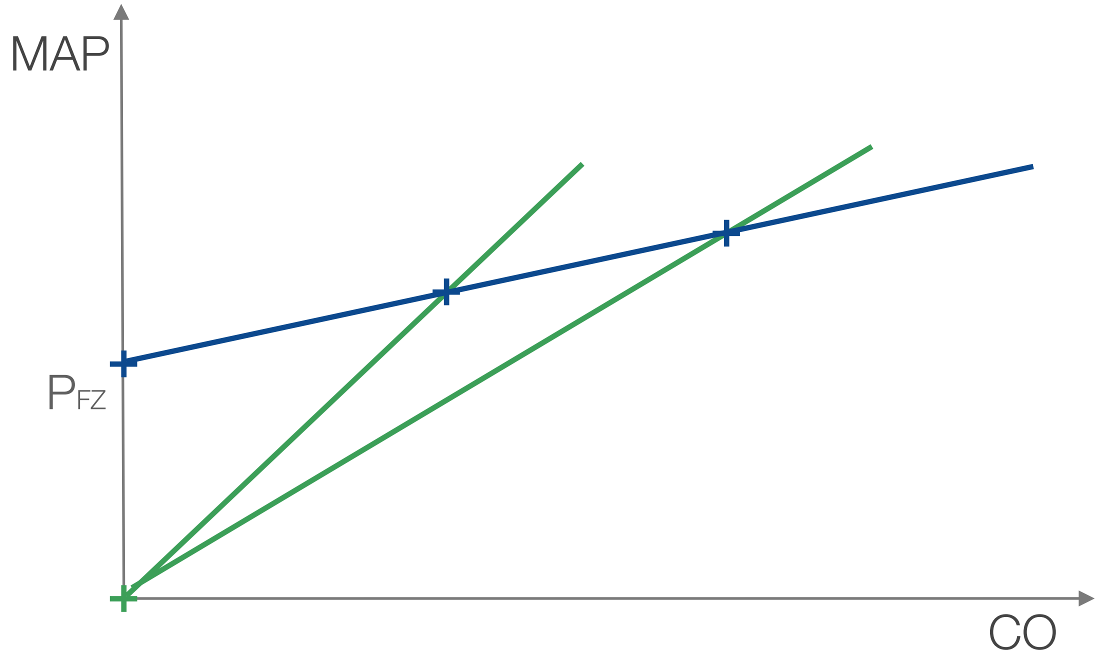
Vascular Tone

Vascular Tone

Ohm's Law $$R = \frac{PD}{I}$$

$$SVR = \frac{(MAP - CVP)}{CO}$$





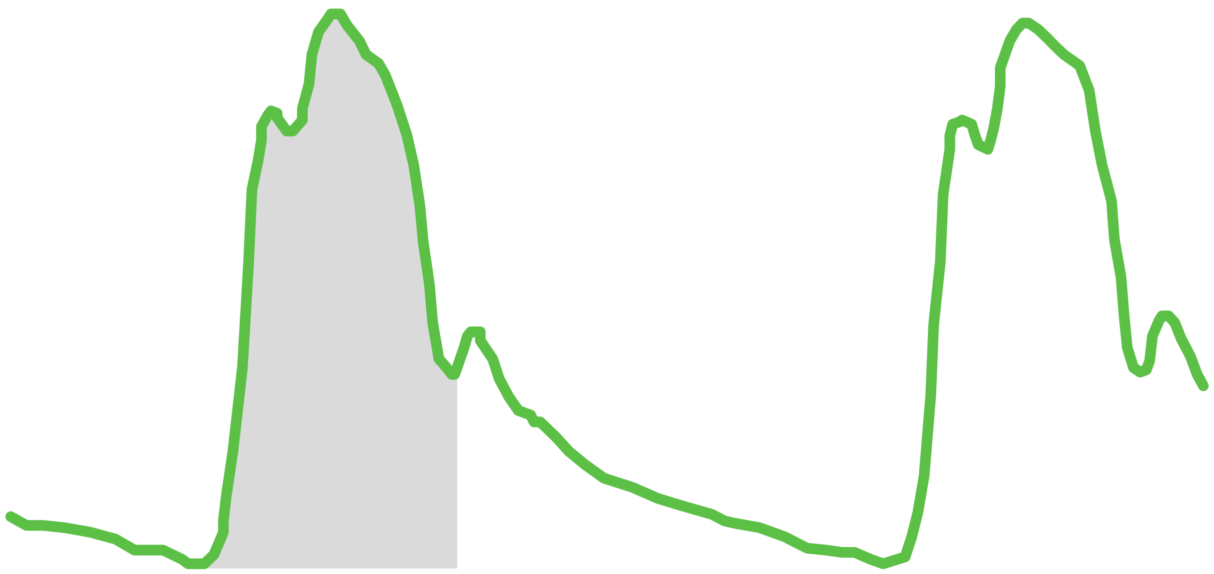
P_{FZ} = Systemic BP at Zero Flow

Continuous Analysis

Continuous Analysis

- Pulse Contour Cardiac Output
- Heart Rate
- Arterial Pressure
- Stroke Volume Index
- Stroke Volume Variation

Calibrated Continuous Pulse Contour Analysis

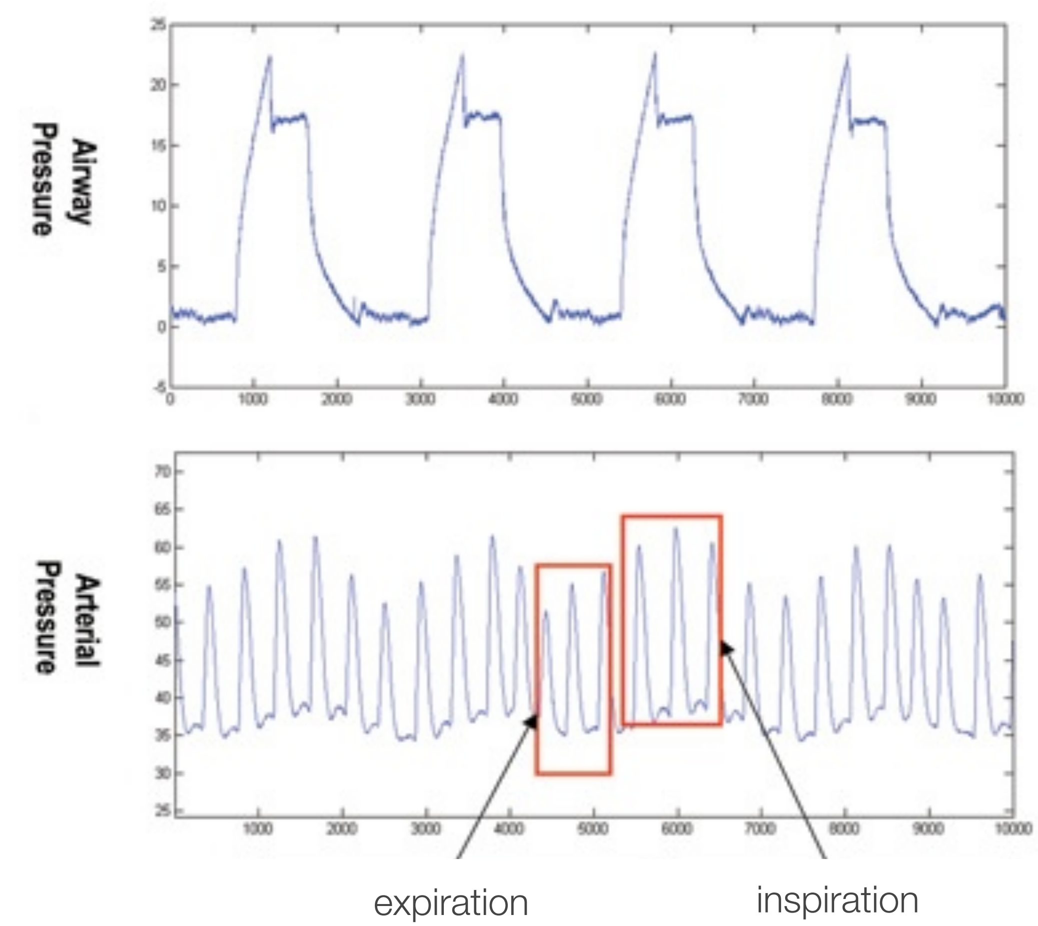


$$\text{Pulse Contour Cardiac Output} = Cal \cdot HR \int_0^{\infty} \left(\frac{P_{(t)}}{SVR} \; C_{(p)} \; \frac{dP}{dt} \right) dt$$

Pulse Pressure / Stroke Volume Variation

$$SVV = \frac{(SV\,max - SV\,min)}{SV\,mean}$$

- Calculated on four 7.5 second epochs averaged over 30 seconds
- Increased in Positive Pressure Ventilation
- Unreliable in cardiac arrhythmia and valve disease

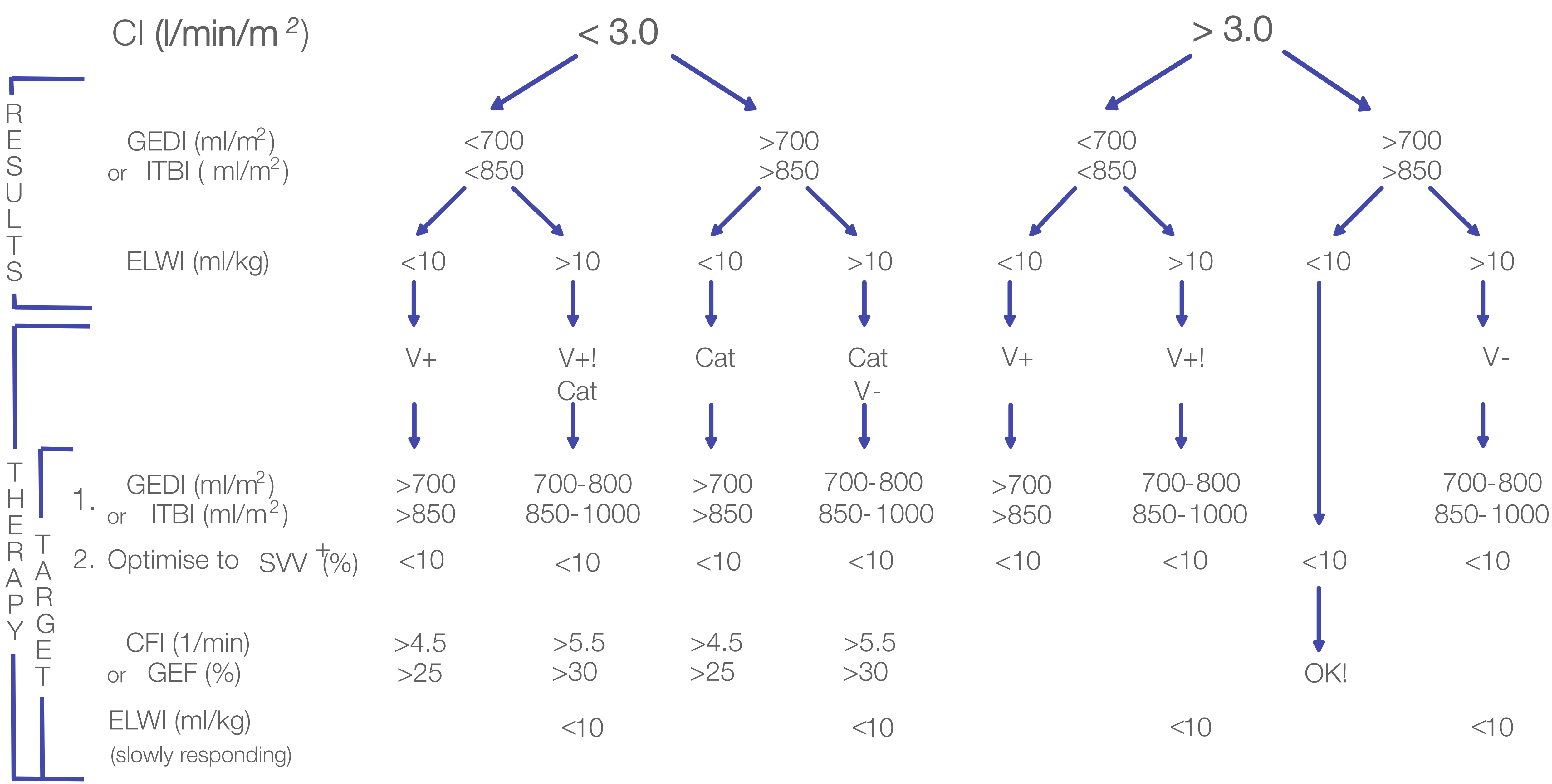


SVV Evidence

	Parameter	Setting	Sensitivity / Specificity
Michard F. *Anesthesiology* 2005; 103:419-428.	PPV	Sepsis	94 / 96
Berkenstadt, et al. *Anesth Analg*. 2001; 92 (4): 984.	SVV	Neurosurgery	79 / 93
Reuter D, et al. *Crit. Care Med* 2003; 31:1300-404.	SVV	Cardiac Surgery	79 / 85

- No evidence in unventilated patients
- Requires regular controlled ventilation
- V_t at least 8 $ml.kg^{-2}$
- If SVV > 13% fluids will work
- If SVV < 6% fluids will not work

PiCCO Decision Tree



The Maths Behind PiCCO™

- Cardiac Function
- PiCCO in Action
- Fluid Distribution
- Vascular Tone
- Calibrated Pulse Contour Analysis

Questions