Haemodynamic Monitoring

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Task of the circulatory system

Pflüger 1872: "The cardio-respiratory system fulfils the physiological task of ensuring cellular oxygen supply"

Haemodynamic monitoring is monitoring whether the circulation is performing its task of oxygen delivery to the tissues.

Goal Reached?

Assessment of oxygen supply and demand

Yes → OK

No → What is the problem?

Diagnosis

Therapy
Processes contributing to cellular oxygen supply

Aim: Optimal Tissue Oxygenation
Organ specific differences in oxygen extraction

Oxygen delivery must always be greater than consumption!

Dependency of Oxygen Demand on delivery

Behaviour of oxygen consumption and the oxygen extraction rate with decreasing oxygen supply

Oxygen consumption

DO$_2$-dependent area

Oxygen extraction rate

DO$_2$-independent area

DO$_2$- dependent area

Decreasing Oxygen Supply

DO$_2$ : Oxygen Delivery
Determinants of Oxygen Delivery and Consumption

Central role of the mixed venous oxygen saturation

Delivery $\text{DO}_2$: $\text{DO}_2 = \text{CO} \times \text{Hb} \times 1.34 \times \text{SaO}_2$

CO: Cardiac Output
Hb: Haemoglobin
SaO$_2$: Arterial Oxygen Saturation
SvO$_2$: Mixed Venous Oxygen Saturation
DO$_2$: Oxygen Delivery
VO$_2$: Oxygen Consumption
Oxygen delivery and its influencing factors

\[ \text{DO}_2 = \text{CaO}_2 \times \text{CO} = \text{Hb} \times 1.34 \times \text{SaO}_2 \times \text{CO} \]

- **Transfusion**
  - CO: Cardiac Output
  - Hb: Haemoglobin
  - \(\text{SaO}_2\): Arterial Oxygen Saturation
  - \(\text{CaO}_2\): Arterial Oxygen Content
Oxygen delivery and its influencing factors

\[ \text{DO}_2 = \text{CaO}_2 \times \text{CO} = \text{Hb} \times 1.34 \times \text{SaO}_2 \times \text{CO} \]

- **Transfusion**
- **Ventilation**

CO: Cardiac Output  
Hb: Haemoglobin  
SaO\(_2\): Arterial Oxygen Saturation  
CaO\(_2\): Arterial Oxygen Content
Oxygen delivery and its influencing factors

\[ \text{DO}_2 = \text{CaO}_2 \times \text{CO} = \text{Hb} \times 1.34 \times \text{SaO}_2 \times \text{CO} \]

- Transfusion
- Ventilation
- Volume
- Catecholamines

Volume Catecholamines

CO: Cardiac Output
Hb: Haemoglobin
SaO\(_2\): Arterial Oxygen Saturation
CaO\(_2\): Arterial Oxygen Content
It's all about

O₂ Delivery
DO₂
Gas exchange?
SaO₂

O₂ Transport?
Hb

Flow?
Cl

Mixed-/Central-Venous O₂ Saturation
ScVO₂

O₂ Consumption
VO₂

Stroke Volume
SVI

Frequency
HR

Preload
GEDI
SVV

Afterload
MAP
SVRI

Contractility
GEF
CFI
Determinants of Oxygen Delivery and Consumption

Central role of mixed central venous oxygen saturation

Delivery $\text{DO}_2$: $\text{DO}_2 = \text{CO} \times \text{Hb} \times 1.34 \times \text{SaO}_2$

Consumption $\text{VO}_2$: $\text{VO}_2 = \text{CO} \times \text{Hb} \times 1.34 \times (\text{SaO}_2 - \text{SvO}_2)$

CO: Cardiac Output
Hb: Haemoglobin
SaO$_2$: Arterial Oxygen Saturation
SvO$_2$: Mixed Venous Oxygen Saturation
DO$_2$: Oxygen Delivery
VO$_2$: Oxygen Consumption
**ScvO\textsubscript{2}**

- Good correlation with SvO\textsubscript{2} (oxygen consumption)
- Surrogate parameter for oxygen extraction
- Information on the oxygen consumption situation
- When compared to SvO\textsubscript{2} less invasive (no pulmonary artery catheter required)
Key Points

• The purpose of the circulation is cellular oxygenation

• For an optimal oxygen supply at the cellular level the macro and micro-circulation as well as the pulmonary gas exchange have to be in optimal balance

• Next to CO, Hb and SaO₂ is SvO₂ which plays a central role in the assessment of oxygen supply and consumption

• No single parameter provides enough information for a full assessment of oxygen supply to the tissues.
Haemodynamic Monitoring

Non-Invasive

- Electrocardiogram (ECG)
- Pulse oximetry (SpO₂)
- NIBP (HR)
Haemodynamic Monitoring

Basic Invasive

Central venous catheter

Arterial catheter
Monitoring of the central venous oxygen saturation

O₂ Therapy and Sedation
Intubation + Ventilation

Central Venous Catheter
Invasive Blood Pressure Monitoring

Cardiovascular Stabilisation

CVP
< 8 mmHg → Volume therapy
8-12 mmHg
< 65 mmHg → Vasopressors
65 mmHg

MAP
< 70% → Blood transfusion to Haematocrit 30%
>70%

ScVO₂
< 70% → Inotropes
>70%

Goal achieved?
no
yes → Therapy maintenance, regular reviews

Early goal-directed therapy
**Key Points**

- Standard monitoring does not give information re the volume status or the adequacy of oxygen delivery and consumption.

- The CVP is not a valid parameter to measure volume status

- The measurement of central venous oxygen saturation gives important information over global oxygenation balance and oxygen extraction

- Measuring the central venous oxygenation can reveal when more advanced monitoring is indicated
Advanced Monitoring

The standard parameters do not give enough information in unstable patients.

What other parameters do I need?
Extended Haemodynamic Monitoring

Therapy

Monitoring

Optimisation
$O_2$ supply
$O_2$ consumption
Haemodynamic Monitoring

Advanced Invasive

- Echocardiography
  - Transthoracic (TTE) or
  - Transesophageal (TEE)

- Pulmonary artery catheter (PAC)

- PiCCO-Technology
PiCCO Technology Set-Up

PiCCO monitoring uses “basic” haemodynamic monitoring but delivers “advanced” haemodynamic monitoring info.
**Principles of PiCCO**

**PiCCO Technology** is a combination of transpulmonary thermodilution and pulse contour analysis indicator = cold
Principles of Measurement

After central venous injection the cold bolus sequentially passes through the various intrathoracic compartments

The temperature change over time is registered by a sensor at the tip of the arterial catheter.
Introduction to the PICCO-Technology – Function

Intrathoracic Compartments (mixing chambers)

Total of mixing chambers: 4 cardiac chambers + pulmonary circulation + EVLW

Total of mixing chambers = intrathoracic thermal volume (ITTV) for indicator (cold)
PiCCO allows the establishment of an adequate cardiac output through optimisation of volume status whilst avoiding lung oedema.
Monitoring – what is the point?

Optimisation of CO

- Preload
- Contractility
- Afterload
- Chronotropy

Frank-Starling mechanism
Preload, CO and Frank-Starling Mechanism

- Volume responsive
- Target area
- Volume overloaded

Normal contractility
Key Points

• The goal of fluid management is the optimisation of cardiac output

• An increase in preload leads to an increase in cardiac output, within certain limits. This is explained by the Frank-Starling mechanism.

• The measurement of cardiac output does not show where the patient’s heart is located on the Frank-Starling curve.

• For optimisation of the CO a valid preload measurement is indispensables.
Calculation of the Cardiac Output

The CO is calculated by analysis of the thermodilution curve using the modified Stewart-Hamilton algorithm:

\[ \text{CO}_{TDa} = \frac{(T_b - T_i) \times V_i \times K}{\int \Delta T_b \times dt} \]

- \( T_b \) = Blood temperature
- \( T_i \) = Injectate temperature
- \( V_i \) = Injectate volume
- \( \int \Delta T_b \cdot dt \) = Area under the thermodilution curve
- \( K \) = Correction constant, made up of specific weight and specific heat of blood and injectate
Thermodilution curves

The area under the thermodilution curve is inversely proportional to the CO.

SHAPE is correlated with CO!

![Diagram showing thermodilution curves for normal, low, and high CO](image)
In both procedures only part of the injected indicator passes the thermistor.

Nonetheless the determination of CO is correct, as it is not the amount of the detected indicator but the difference in temperature over time that is relevant.
Extended analysis of the thermodilution curve

From the characteristics of the thermodilution curve it is possible to determine certain time parameters

**MTt: Mean Transit time**
the mean time required for the indicator to reach the detection point (75% of its maximum)

**DSt: Down Slope time**
the exponential downslope time of the thermodilution curve from 75% of its maximum to 25% of its maximum

Represented “mixing behaviour” of the indicator in the largest single mixing chamber

$T_b = \text{blood temperature}; \ln T_b = \text{logarithmic blood temperature}; t = \text{time}$
Calculation of ITTV and PTV

By using the time parameters from the thermodilution curve and the CO ITTV and PTV can be calculated

\[ \text{PTV} = Dst \times \text{CO} \]

Calculation of ITTV and PTV

\[ \text{ITTV} = MTt \times \text{CO} \]

ITTV correlates with distribution volume for the indicator ("cold")
Key Points - Thermodilution

- PiCCO Technology is a less invasive method for monitoring the volume status and cardiovascular function.
- Transpulmonary thermodilution allows calculation of various volumetric parameters.
- The CO is calculated from the shape of the thermodilution curve.
- The volumetric parameters of cardiac preload can be calculated through advanced analysis of the thermodilution curve.
- For the thermodilution measurement only a fraction of the total injected indicator needs to pass the detection site, as it is only the change in temperature over time that is relevant.
Calibration of the Pulse Contour Analysis

The pulse contour analysis is calibrated through the transpulmonary thermodilution and is a beat to beat real time analysis of the arterial pressure curve.

The SV obtained with thermodilution is placed in relation to the AUC under the systolic part of the arterial pulse curve.

Using this calibration, CO can be determined continuously from the arterial pressure curve (pulse contour).

\[
\text{CO}_{\text{TPD}} = \frac{\text{SV}_{\text{TD}}}{\text{HR}}
\]

\( T \) = blood temperature
\( t \) = time
\( P \) = blood pressure
Parameters of Pulse Contour Analysis

Cardiac Output

\[ PCCO = \text{cal} \cdot HR \cdot \int \left( \frac{P(t)}{SVR} + C(p) \cdot \frac{dP}{dt} \right) \, dt \]

- **Patient-specific calibration factor** (determined by thermodilution)
- **Heart rate**
- **Area under the pressure curve**
- **Aortic compliance**
- **Shape of the pressure curve**
Volumetric Preload Parameters, Volume Responsiveness and Filling Pressures

- Filling Pressures: CVP / PCWP
- Volumetric Preload parameters: GEDV / ITBV
- Volume Responsiveness: SVV / PPV
Physiology of the dynamic parameters of volume responsiveness

Fluctuations in blood pressure during the respiration cycle

**Early Inspiration**
- Intrathoracic pressure ↑
- "Squeezing" of the pulmonary blood
- Venous return to left and right ventricle ↓
- Left ventricular preload ↑
- Left ventricular stroke volume ↑
- Systolic arterial blood pressure ↑

**Late Inspiration**
- Intrathoracic pressure ↑
- Venous return to left and right ventricle ↓
- Left ventricular preload ↓
- Left ventricular stroke volume ↓
- Systolic arterial blood pressure ↓

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Reuter et al., Anästhesist 2003;52: 1005-1013
Physiology of the dynamic parameters of volume responsiveness

Fluctuations in stroke volume throughout the respiratory cycle

Mechanical Ventilation

- Intrathoracic pressure fluctuations
- Changes in intrathoracic blood volume
- Preload changes
- Fluctuations in stroke volume
The Stroke Volume Variation is the variation in stroke volume over the ventilatory cycle, measured over the previous 30 second period.
Parameters of Pulse Contour Analysis

Dynamic parameters of volume responsiveness – Pulse Pressure Variation

The pulse pressure variation is the variation in pulse pressure over the ventilatory cycle, measured over the previous 30 second period.

\[ PPV = \frac{PP_{\text{max}} - PP_{\text{min}}}{PP_{\text{mean}}} \]
Role of the dynamic volume responsiveness parameters  SVV / PPV

SVV is more accurate for predicting volume responsiveness than CVP

Summary pulse contour analysis - CO and volume responsiveness

- The PiCCO technology pulse contour analysis is calibrated by transpulmonary thermodilution
- PiCCO technology analyses the arterial pressure curve beat by beat thereby providing real time parameters
- Besides cardiac output, the dynamic parameters of volume responsiveness SVV (stroke volume variation) and PPV (pulse pressure variation) are determined continuously
Role of the dynamic volume responsiveness parameters  SVV / PPV

The dynamic volume responsiveness parameters SVV and PPV

- are good predictors of a potential increase in CO due to volume administration
- are only valid with patients who are fully ventilated and who have no cardiac arrhythmias
The Extravascular Lung Water is the difference between the intrathoracic thermal volume and the intrathoracic blood volume. It represents the amount of water in the lungs outside the blood vessels.
EVLW as a quantifier of lung oedema

Extravascular lung water index (ELWI) normal range: 3 – 7 ml/kg

ELWI = 19 ml/kg

ELWI = 7 ml/kg

ELWI = 14 ml/kg

ELWI = 8 ml/kg
PiCCO allows the establishment of an adequate cardiac output through optimisation of volume status whilst avoiding lung oedema
Therapy Guidance with PiCCO Technology

PiCCO monitoring
CI, Preload, Contractility, Afterload, Volume responsiveness

Evaluation of therapy success

Therapy
Volume / Catecholamines

if necessary: additional information
Oxygen extraction ScvO₂
Validation PiCCO technology

Table 2. Comparisons of Transcardiopulmonary Thermodilution Versus Pulmonary Artery Thermodilution
Cardiac Output

<table>
<thead>
<tr>
<th>Investigators (y)</th>
<th>Study variables</th>
<th>Measures of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patient population</td>
<td>Ages</td>
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<tr>
<td>Della Rocca et al. 2002128</td>
<td>Liver transplant</td>
<td>24-66</td>
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<td>Friesecke et al. 2009129</td>
<td>Severe heart failure</td>
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<tr>
<td>Goedje et al. 199987</td>
<td>Cardiac surgery</td>
<td>41-81</td>
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<td>Holm et al. 200185</td>
<td>Burns</td>
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<td>Kuntscher 200286</td>
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<td>McLuckie et al. 199684</td>
<td>Pediatrics</td>
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<td>Segal 200281</td>
<td>Intensive care unit</td>
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<td>von Spiegel et al. 199680</td>
<td>Cardiology</td>
<td>0.5-25</td>
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<tr>
<td>Wiesenack et al. 2001130</td>
<td>Cardiac surgery</td>
<td>43-73</td>
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<tr>
<td>Zöllner et al. 199987</td>
<td>ARDS</td>
<td>19-75</td>
</tr>
</tbody>
</table>

N = number of patients; n = number of measurements; Precision = sd of differences, if not otherwise noted; ni = not indicated.
Limitations of PiCCO parameters – pulse contour analysis

Knowledge of the limitations is essential for correct interpretation of the data!

SVV / PPV can only be used with fully controlled mechanical ventilation (minimal tidal volume 6-8ml/kg) and absence of cardiac arrhythmias (otherwise may give false high reading)

All parameters of pulse contour analysis not valid when an IABP is in use (thermodilution is unaffected)
PiCCO Technology in special situations

Renal replacement therapy: normally no interference with the PiCCO parameters

Prone positioning: all parameters are measured correctly

Peripheral venous injection: not recommended, measurements possibly incorrect
Contraindications to PiCCO Technology

Because of the low invasiveness there are no absolute contraindications

The usual precautions are required when puncturing larger blood vessels:
• coagulation disorders
• vascular prosthesis (use other puncture site, e.g. axillary)