Non-invasive and Minimally-invasive Hemodynamic Monitors
Christoph K. Hofer, MD DEAA
Institute of Anesthesiology and Intensive Care Medicine
Triemli City Hospital Zurich
Birmensdorferstr. 497, 8063 Zurich, Switzerland
Email: christoph.hofer@triemli.stzh.ch

Learning objectives
1. The participant will be able to describe the technical principles of the major groups
minimally invasive hemodynamic monitors.
2. In addition, the participant will be able to apply an integrated approach for the use of
different devices in the perioperative setting based on invasiveness, typical limitations,
and specific hemodynamic variables.

Introduction
Hemodynamic monitoring is typically performed to ensure tissue oxygenation in critically
ill patients in different settings. Until recently the pulmonary artery catheter (PAC) was
widely used for this task in order to assess cardiac output (CO), the primary determinant
of oxygen delivery. Today, a variety of minimally invasive hemodynamic monitors are
available decreasing the widespread PAC use (1). These techniques provide information
of systemic flow and cardiac performance as well as intravascular fluid status.

General remarks
1. Some minimally invasive techniques track stroke volume (SV) continuously and
provide dynamic indices of fluid responsiveness; others allow the assessment of
volumetric preload variables, and some the continuous measurement of central
venous saturation with proprietary catheters (2). These hemodynamic variables in
combination with CO may allow an improved hemodynamic assessment.
2. There is no “best” monitoring technique and the inherent limitations of each minimally
invasive technique have to be considered when they are applied. Performance of all
non- and minimally-invasive monitors has been shown to be quite similar when
compared to the clinical standard, the PAC (3).
3. In general it can be assumed, that reliability and accuracy of CO measurements
decreases with increasing “non-invasiveness”. In clinical practice however, CO trends
are more important than absolute values. Moreover, all available hemodynamic
variables as well as the patient examination have to be considered in clinical decision-
making.
4. Echocardiography can be considered a minimally invasive hemodynamic monitor that
enables visualization of cardiac anatomy and function and should always be
performed when hemodynamic instability of unknown etiology occurs. Moreover, a
new transesophageal echocardiography device with a miniaturized probe (ImaCor Inc,
Garden City NY) may now be used for continuous hemodynamic assessment.
5. No monitoring technique can positively influence patient outcome per se unless its use
is coupled with an adequate treatment protocol (4).

Monitors
Minimally invasive CO monitoring devices (Table 1) use one of four principles to assess
CO / SV:
A. Pulse wave analysis
B. Pulsed Doppler technology
C. Bioimpedance / Bioreactance
D. Applied Fick’s principle
A. Pulse wave analysis

Pulse wave analysis derives CO/SV from continuous pressure waveform measurement via an arterial line. The characteristics of the arterial pressure waveform are determined by the interaction between cardiac action and vascular compliance, aortic impedance as well as peripheral arterial resistance (2). For adequate CO/SV measurement some features and limitations need to be considered:

1. Optimal arterial waveform signal is a prerequisite, i.e. damping or increased tubing resonance has to be eliminated or at least reduced.
2. Severe arrhythmias and the use of an intra-aortic balloon pump impede adequate performance of pulse wave analysis.
3. Rapid changes of vascular resistance may limit reliable CO/SV measurements. This can be especially a problem for the un-calibrated devices. By contrast, calibrated devices require frequent re-calibration for accurate CO estimation under these conditions.
4. Severe atherosclerosis may preclude the insertion of an arterial catheter or reliable measurements (e.g. subclavian stenosis and signal detection via radial arterial line).

Different calibrated and un-calibrated devices are currently available. These are described in the following section.

PiCCO2

The PiCCO2 system (Pulsion Medical Systems, Munich, Germany) requires a dedicated thermistor-tipped catheter that is typically placed in the femoral artery, in order to assess SV on a beat-to-beat basis. The PiCCO algorithm assumes that the area under the systolic part of the pressure curve corresponds with SV. A calibration is required that is performed using intermittent trans-pulmonary thermo-dilution via a central venous line. The calibration process enables also for the adjustment of individual aortic impedance. It has to be repeated every 8h in hemodynamically stable patients and during situations of hemodynamic instability calibration needs to be done more frequently (5). The recently launched un-calibrated device (PulsioFlex) uses a specific arterial pressure sensor that can be connected to a regular invasive arterial pressure monitoring set. CO/SV is estimated using an algorithm similar to the PiCCO2 system, but requires a hemodynamic database ("nomogram") in order to eliminate calibration.

LiDCOplus / LiDCOrapid

The LiDCOplus and LiDCOrapid systems (LiDCO Ltd, London, UK) are based on the same pulse pressure algorithm (PulseCO) and track SV continuously. This algorithm is based on the assumption that net power change in the vascular system is the difference of the amount of blood entering the system (i.e. SV) minus the amount of blood flowing peripherally and that there is a linear relationship between net power and netflow. The LiDCOplus requires calibration by the transpulmonary lithium indicator dilution technique, which can be performed via a peripheral venous line. By contrast, the LiDCOrapid does not require calibration because CO estimation relies on hemodynamic nomograms.

FloTrac / Vigileo / EV1000

The FloTrac /Vigileo system (Edwards LifeSciences, Irvine, CA USA) requires a proprietary transducer, the FloTrac, which is attached to a standard non-proprietary radial or femoral arterial catheter and is connected to the Vigileo monitor. The FloTrac /Vigileo system does not require calibration. In order to assess CO, the standard deviation of pulse pressure sampled during a time window of 20 seconds is correlated with ‘normal’ SV based on patient’s demographic data (age, gender,
height, and weight) and a built-in database containing information regarding CO assessed by PAC in a variety of clinical scenarios. Impedance is also derived from these data whereas vascular compliance and resistance are determined using arterial waveform analysis. A new CO monitoring device based on pulse pressure analysis that is calibrated by transpulmonary thermodilution, the EV 1000 platform with the VolumeView arterial catheter, has been recently released in Europe.

**CCNexfin**
The CCNexfin (BMEYE B.V, Amsterdam, Netherlands) is a completely non-invasive pulse pressure analysis device, which monitors pulse pressure using photoelectric plethysmography in combination with a volume-clamp technique, i.e. an inflatable finger cuff system. It is the only device that provides continuous information on oxygen delivery via incorporated pulse oximetry.

**B. Doppler CO monitoring devices**
Different *esophageal Doppler* probes are available, for example the ODM II (Abbott, Maidenhead, UK) and the CardioQ (Deltex Medical Ltd, Chichester, Sussex, UK). Another device the HemoSonic100 (Arrow, Reading, PA, USA), which is a combination of a Doppler and an M-mode probe, is not produced anymore. Esophageal Doppler devices measure blood flow in the descending aorta and derive CO by multiplying the cross sectional area of the aorta by blood flow velocity. The aortic diameter is obtained from nomograms or by direct measurement using M-mode echocardiography. There are several important limitations for the use of esophageal Doppler devices:

1. Doppler devices assume a fixed partition between flow to the cephalic vessels and to the descending aorta. This may be a valid assumption in healthy volunteers, however the relationship may change in patients with co-morbidities and under conditions of hemodynamic instability.
2. Doppler probes are smaller than the conventional trans-esophageal echocardiography probes. Therefore, probe position may change unintentionally and continuous monitoring is restricted.
3. The device is operator-dependent and studies have shown that roughly 12 insertions are required to obtain accurate measurements with an acceptable intra- and inter-observer variability (6).
4. Aortic cross-sectional area is not constant but rather dynamic in any individual patient. Therefore, the use of nomograms may result in less accurate measurements.

As an alternative to the esophageal approach, the *transthoracic* may be used to assess CO. The USCOM device (USCOM, Sidney, Australia) targets the pulmonary and aortic valves accessed via the parasternal and suprasternal windows in order to assess CO completely non-invasively. Unfortunately, no continuous measurement is possible.

**C. Bioimpedance and Bioreactance**

*Electrical bioimpedance* uses electric current stimulation for the identification of thoracic impedance amplitude variations that are induced by cyclic changes in blood flow caused by the heart beating. CO is estimated, using skin electrodes or electrodes mounted on an endotracheal tube, by analyzing the occurring signal variation based on different mathematical models. *Bioreactance* (Cheetah Medical Inc. Portland, OR, USA), on the other hand, is a modification of the thoracic bioimpedance that analyzes the frequency spectra variations of the delivered oscillating current. This is supposed to result in a high signal-to-noise ratio and thus
in an improved performance of the technique. Limitations of these techniques include:

1. The different algorithms cannot compensate for intrathoracic fluid shifts, which impede the clinical use in patients with severe cardio-pulmonary disease.
2. Assumptions are made for SV estimation that may induce a considerable error in an individual patient.
3. The technique is prone electrical artefacts especially in the OR. Moreover, electrode localisation may influence measurements (e.g. inferior results with endotracheal tube electrodes).

**D. Applied Fick’s principle: Partial CO2 re-breathing**

The NICO system (Novametrix Medical Systems, Wallingford, USA) applies the Fick’s principle to carbon dioxide (CO2) for CO measurement in intubated, sedated, and mechanically ventilated patients using a disposable re-breathing loop that is attached to the ventilator circuit. There are some limitations to partial CO2 re-breathing:

1. It can reliably perform CO measurement only in intubated and mechanically ventilated patients with fixed ventilator settings.
2. Patients with gas exchange abnormalities need to be excluded from monitoring.
3. CO is determined every 3 min via a partial re-breathing state. Therefore, no continuous monitoring is possible.

**Additional hemodynamic variables**

Apart from SV and CO hemodynamic monitoring devices provide various additional hemodynamic variables (Table 1):

A. Static preload variables
B. Functional hemodynamic variables
C. Continuous central venous oxygen saturation (ScvO2) using a dedicated catheter

**A. Static preload variables**

**Pressure preload variables**

Central venous pressure (CVP) is still widely assessed today as an estimate of cardiac preload and CVP measurement is often easily available because some CO monitors require a central venous line for system calibration. However, for a correct and reliable clinical use some important issues have to be considered:

1. True preload is defined as end-diastolic myocardial fiber tension that cannot be directly assessed at the bedside. Interestingly, several studies have shown a lack of correlation between CVP and echocardiographic preload estimates (8).
2. Factors that affect CVP include impaired right ventricular function, severe pulmonary or valvular heart disease as well as positive pressure ventilation or increased intra-abdominal pressure.
3. CVP is not able to reliably predict preload responsiveness (9).
4. CVP changes in trend over time may be more important than absolute CVP in order to guide therapy.

**Volumetric preload variables**

The so-called volumetric preload variables are considered to be superior indicators of preload as compared to CVP or pulmonary capillary wedge pressure. Typical static volumetric parameters are global end-diastolic volume (GEDV) and extravascular lung water (EVLW). These are determined by transpulmonary thermodilution, which is required for the calibration of the PiCCO2 device and the EV1000 system. GEDV has shown to be a better preload parameter than between the static pressure parameters. However, it cannot be used to predict fluid responsiveness. EVLW on
the other hand may be used to differentiate between cardiac vs. non-cardiac pulmonary edema, and has been identified as an independent predictor of survival in critically ill patients (10).

B. Functional hemodynamic variables
Pulse pressure analysis devices provide an automated quantification of stroke volume variation (SVV) and some also pulse pressure variation (PPV). These functional variables rely on cyclic changes in intrathoracic pressure during positive pressure ventilation which induce changes in stroke volume and pulse pressure as a result of a reduction in preload. In contrast to static preload variables they have been shown in various studies to be able to predict fluid responsiveness (11). However the reliability of these variables is limited under different cardiovascular and ventilatory conditions.

1. Sever cardiac arrhythmia
2. Right heart failure
3. Spontaneous breathing activity
4. Low tidal volume (< 8 ml/kg body weight)

Alternatively, “passive leg raising” may be used to assess fluid responsiveness. (12)

C. Central venous oxygen saturation (ScvO₂)
ScvO₂ can be used as global marker of the balance between systemic oxygen supply and demand. Compared to mixed venous oxygen saturation (SvO₂) that requires the placement of a pulmonary artery catheter ScvO₂ can be easily measured by blood gas analysis using a sample drawn from a central venous catheter. Additionally, both ScvO₂ and SvO₂ can be assessed continuously using proprietary central venous and pulmonary artery catheters, respectively. These central venous catheters are available for the Vigileo and the PiCCO systems. Absolute ScvO₂ and SvO₂ values may differ considerably in different clinical situations but a strong correlation of their trends over time has been demonstrated (13).

Integrative concept
No single device can comply with all clinical requirements considering the technical features and limitations of the different monitoring techniques (36). Thus, different devices need to be used in an integrative concept along a clinical patient pathway of thoracic surgery (Figure 1) based on the invasiveness of the devices and the additional hemodynamic variables (Table 1).

1. Bioimpedance and Bioreactance have both the potential to be primarily used on the ward for improved patient assessment.
2. Un-calibrated pulse wave analysis devices are the first choice for the daily routine in a perioperative setting because they provide functional hemodynamic variables and allow a comprehensive hemodynamic management on a minimally invasive basis.
3. Calibrated pulse wave analysis systems may be required when postoperative complications or hemodynamic instability are expected and increased accuracy of the device or volumetric variables are needed.
4. PAC insertion is mandatory for patient specific therapy when limited accuracy of minimally invasive monitoring devices is suspected and when pulmonary artery pressure monitoring or right heart failure treatment is required.
5. Echocardiography should always be performed when hemodynamic instability of unknown etiology occurs, but may be used more often today on a regular basis with smaller probes and user-optimized devices.
Summary
Different techniques provide continuous CO measurement on a minimally invasive basis. A variety of factors influence the choice of a minimally invasive technique and clinicians need to understand the underlying principles and the inherent limitations. Based on these principles and limitations several minimally invasive techniques may be used in an integrative approach. In combination with ScvO₂ measurement, volumetric preload assessment, functional variables and echocardiographic assessment these techniques may obviate the need for a PAC.

References
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Legend: CO = Cardiac Output, CVP = Central Venous Pressure, EVLW = Extravascular Lung Water, GEDV = Global End-Diastolic Volume, NA = Information not available, PPV = Pulse Pressure Variation, SCVO₂ = Central Venous Oxygen Saturation, SVV = Stroke Volume Variation, TE = Trans-Esophageal, TT = Trans-Thoracic
Figure 1: Integrative hemodynamic concept