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Perioperative haemodynamic optimisation in patients undergoing non-cardiac surgery — a position statement from the Cardiac and Thoracic Anaesthesia Section of the Polish Society of Anaesthesiology and Intensive Therapy. Part 2

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METHODS TO MONITOR CARDIOVASCULAR FUNCTION AND DYNAMICS

Cardiovascular monitoring is usually based on continuous electrocardiographic (ECG) recording and periodic indirect blood pressure measurements. With an increasing risk of postoperative complications, additional measures usually include cannulation of a central vein and the radial artery, which permits measurements of central venous pressure and continuous invasive blood pressure measurements, with a possibility to evaluate temporal changes and trends in the recorded curves. Although treatment guided by these parameters is mostly targeted at achieving and maintaining normal blood pressure values, the volume of oxygenated blood reaching end organs may not be directly related to arterial blood pressure. Vasoconstriction may lead to blood pressure normalization despite poor organ perfusion, particularly in view of the significant adaptive capabilities of the vascular system. On the other hand, reduced autonomic system tone during anaesthesia leads to blood pressure reduction even with normal intravascular volume.

Only three types of therapies affecting the cardiovascular system are at the anaesthesiologist's disposal in the operating room: infusing fluids, administering drugs that increase myocardial contractility (positive inotropic agents), as well as administering vasoactive agents that affect the degree of vessel constriction. In the case of all these three therapies, although the timing of the treatment and the doses used are of key importance for preventing cardiovascular decompensation, improving organ perfusion is not always possible.

The most important factor determining adequate cardiovascular function is cardiac output, or the volume of the blood ejected from the heart per minute. However, evaluation of myocardial performance should always be based on stroke volume (SV), so as not to miss a situation when cardiac output is preserved by increasing heart rate but at the cost of stroke volume reduction. Stroke volume depends mostly on the force of myocardial contraction and the end-diastolic volume. Thus, even a normally contracting heart will not generate adequate cardiac output without adequate intravascular volume regardless of whether the cause is actual (absolute) hypovolaemia (due to bleeding or dehydration), or relative hypovolaemia due to vasodilation. In turn, even a normally contracting heart may not work effectively against increased afterload induced by large doses of vasoconstricting agents. Thus, the stability of the cardiovascular system depends on

Table 1. Fick's method

Advantages	**Most precise method to measure cardiac output**
Disadvantages	Complicated, time-consuming, very invasive method. Obtaining all necessary parameters requires a cannula in a peripheral artery, pulmonary artery catheter, and a closed ventilation system
Indications	Reference method used in comparative studies

several interrelated factors: cardiac output is determined by myocardial contractility and adequate intravascular volume, which, in turn, depends on the absolute blood volume and the degree of vessel constriction.

METHODS OF CARDIAC OUTPUT MEASUREMENT

Many tools and techniques are available to measure cardiac output [1–5]. They are all based on one of the following five methods.

METHOD #1. FICK'S LAW

This is based on the law of conservation of mass and is the oldest known method to measure cardiac output. If an indicator is added to the venous system at a known rate (X_r), and the blood level of the indicator may be measured, the velocity of blood flow may be measured if the venous and arterial blood levels of the indicator are known. The amount of the indicator in the arterial system (X_a) is equal to the amount of the indicator returning within the venous system (X_v) plus the amount added to the circuit in a unit of time ($X_a=X_v+X_r$). As oxygen was the indicator in the original Fick's law, the calculation should include tissue oxygen uptake. Thus, we get an equation:

The amount of oxygen in the arterial system ($CO \times CaO_2$) is equal to the amount of oxygen in the venous system ($CO \times CvO_2$) plus tissue oxygen uptake (VO_2)

$$CO \times CaO_2 = (CO \times CvO_2) + VO_2$$

By measuring oxygen content in the arterial and venous blood and oxygen uptake, it is possible to measure cardiac output precisely:

$$CO = VO_2 / CaO_2 - CvO_2$$

Where CO is cardiac output, VO_2 is oxygen uptake, CaO_2 is oxygen content in the arterial blood, and CvO_2 is oxygen content in the venous blood.

In clinical practice, obtaining these data is quite complicated. The amount of oxygen in the arterial blood is most readily available (arterial blood gases). To evaluate the amount of oxygen in the mixed venous blood, a sample must be collected from the pulmonary artery via a Swan-Ganz catheter. However, carrying out a reliable measurement of actual oxygen uptake is the most complicated procedure as this requires a closed ventilation system. However, the last measurement may be omitted and a constant value of VO_2 = 125 mL $min^{-1}m^{-2}$ (resting oxygen uptake) may be used in the equation. Cardiac output estimated this way becomes less precise due to the patient's varying metabolic status (Table 1).

NICO (NON-INVASIVE CARDIAC OUTPUT)

Using carbon dioxide as indicator in the Fick equation allowed non-invasive measurements of cardiac output in ventilated patients. In this case, the amount of the indicator in venous blood increases by the amount of CO_2 generated in tissues. Thus, the equation now becomes:

The amount of CO_2 in the venous system ($CO \times CvCO_2$) is equal to the amount of CO_2 in the arterial system ($CO \times CvCO_2$) plus CO_2 production due to cellular respiration (VCO_2)

$$CO \times CvCO_2 = (CO \times CaCO_2) + VCO_2$$

$$CO = VCO_2 / CvCO_2 - CaCO_2$$

Where CO is cardiac output, VCO_2 is exhaled CO_2, $CvCO_2$ is CO_2 content in the venous blood, and $CaCO_2$ is CO_2 content in the arterial blood.

VCO_2 is the amount of exhaled CO_2 measured in the exhaled air. CO_2 content in the arterial blood may be obtained by comparing the end-tidal CO_2 level ($etCO_2$) with CO_2 dissociation curve. CO_2 content in the venous blood is most difficult variable to measure. To eliminate the need for this measurement, the described method used additional tubing in the ventilator system and a valve that opened for several seconds, allowing the passage of gas through this route. A bypass was then created, diverting some exhaled air directly to the inspiration arm. During this time, the CO_2 level in the arterial blood (pCO_2) and the amount of CO_2 in the respiratory system ($etCO_2$) change slightly while CO_2 in the venous blood remains similar. By comparing the Fick equation for these two systems, a differential equation may be obtained:

$$CO = \Delta VCO_2 / S \times \Delta etCO_2$$

Where S is the CO_2 dissociation curve constant.

In this method, the patient must be intubated, and calculations are based on the portion of blood that participates in gas exchange in the lungs. With a large pulmonary shunt, the result is not reliable (e.g. gas diffusion disturbances in respiratory failure) which is a major limitation of this method (Table 2).

Table 2. NICO

Available technologies → NICO (Philips Respironics, the Netherlands)	
Advantages	Continuous measurement of cardiac output Additional measurement: CO_2 elimination rate, pulmonary capillary flow rate
Disadvantages	Patient intubated, sedated, and ventilated Measurement affected by large ventilation/perfusion mismatch, large pulmonary shunt (pneumonia, atelectasis) Poor correlation with thermodilution methods Risk of increasing $etCO_2$ (effect on intracranial pressure?)
Indications	Selected clinical situations in ICU (patients in deep sedation, ventilated, without respiratory disease)

$etCO_2$ — amount of CO_2 in the respiratory system

METHOD #2. INDICATOR DILUTION (DILUTION METHODS)

Indicator dilution methods used to measure cardiac output are mostly based on temperature measurements (thermodilution). A thermometer is introduced to a blood vessel. If a known volume of fluid with a temperature lower than that of the moving blood is injected proximally, a transient drop in blood temperature will be recorded at the measurement site. The higher is the flow rate, the more rapid are changes measured by the thermometer until the temperature returns to the baseline, which may be depicted on a curve showing temperature changes over time. Using the Stewart-Hamilton algorithm, the area under the curve allows for calculating the blood flow rate in the vessel, or cardiac output (Fig. 1).

Right-heart thermodilution

A pulmonary artery (Swan-Ganz) catheter with a thermometer (placed beyond the pulmonary valve) is needed for this measurement. Following indicator injection (cooler fluid) to the right atrium, the rate of temperature change in the pulmonary artery (which depends on cardiac output generated by the right ventricle) is measured and cardiac output is calculated.

Swan-Ganz catheter with continuous measurement — in this method, warmed patient blood is used as the indicator. The modification involves mounting a heating coil on the catheter which sequentially warms the moving blood slightly every minute or so. Measurement is thus automated

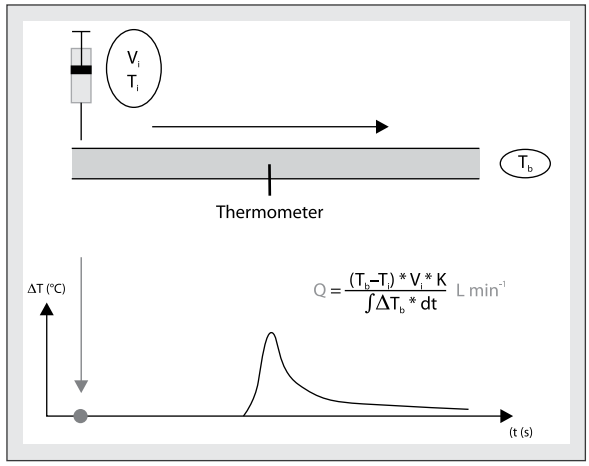

Figure 1. Principles of the dilution methods

Table 3. Swan-Ganz catheter-based thermodilution methods

Available technologies → Swan-Ganz catheter (many manufacturers)/modified Swan-Ganz catheter with continuous measurement (Vigilance, Edwards Lifesciences, USA)	
Advantages	Precise measurement of cardiac output, including patients breathing spontaneously, with cardiac arrhythmia, intra-aortic balloon counterpulsation, receiving high doses of vasoactive drugs, with chest drainage With the modified catheter, there is no need to administer cooler fluid and sequential measurements are possible (every several minutes) Additional advantages: the only method that allows direct evaluation of the pulmonary circulation (pulmonary vascular resistance, pulmonary artery pressure, pulmonary capillary wedge pressure)/the only method that allows mixed venous blood sampling/with the modified catheter, additional measurement of right ventricular end-diastolic volume and right ventricular ejection fraction
Disadvantages	High level of invasiveness and risk of complications Possible interpretation errors (sources of error — catheter tip positioning, measurements during appropriate respiratory cycle phase, artifacts associated with administration of the indicator) With the modified catheter – high cost/measurements every several minutes, and not beat-to-beat
Indications	Cardiac surgery, thoracic surgery, chest organ transplantation Patients with pulmonary hypertension Patients with right ventricular failure Contraindications to other measurement methods

Table 4. Dilution methods — transpulmonary thermodilution

Available technologies → Transpulmonary thermodilution (PICCO-Technology, Pulsion, Maquet, USA; Volume View EV1000, Edwards Lifesciences, USA)/Lithium dilution cardiac output (LiDCOLdt, United Kingdom)	
Advantages	High agreement with right-heart thermodilution methods Additional measurements allowed by transpulmonary indicator passage: cardiac preload (volume parameters)/cardiac function/ /extravascular lung water and differential diagnosis of pulmonary oedema Combines two measurement methods: dilution and calibrated pulse wave analysis (see APCO methods) Calibrated APCO: continuous measurement of cardiac output/evaluation of dynamic parameters of intravascular volume
Disadvantages	Invasiveness and risk of complications due to central venous catheter and large artery cannulation Measurements disturbed by severe vasoconstriction, intra-aortic balloon counterpulsation, significant aortic valve disease, continuous renal replacement therapy (with superior vena cava cannulation)
Indications	Shock of various aetiology/ARDS /burns/high-risk surgical procedures ICU patients in whom evaluation of pulmonary circulation is not necessary

APCO — arterial pressure-based cardiac output; ARDS — acute respiratory distress syndrome.

without the need to administer cooler fluid and cardiac output may be measured continuously (Table 3).

Transpulmonary thermodilution

This method is based on the same principles as above. It involves injecting a cool indicator fluid to the right atrium through a distal ending of a central catheter. The difference is the location of the temperature probe which is placed in the arterial system beyond the aortic valve, most commonly in the femoral artery. The injected indicator travels a much longer distance, including the pulmonary circulation and the left heart, to the place where temperature is recorded for the purpose of cardiac output calculation. For reliable measurements, is it necessary to use a larger indicator fluid volume, while the temperature difference between the blood and the indicator fluid must be higher.

Lithium dilution cardiac output (LiDCO)

Dilution methods may also be based on other indicators than cooled saline. In the LiDCO method, analogously to transpulmonary thermodilution, a solution containing a small amount of lithium chloride is injected into the right atrium. The lithium level in the blood ejected by the left ventricle is measured by a probe mounted on an arterial catheter. The rate of lithium level change at the measurement site depends on the blood flow rate. Cardiac output is calculated from the area under the curve of lithium level changes with time, analogously to thermodilution methods (Table 4).

METHOD #3. PULSE WAVE ANALYSIS (TABLE 5)

Cardiac output may be calculated based on the arterial pressure curve, as stroke volume is proportional to the area under the curve in the systolic phase. The end of the systolic phase is seen as a dicrotic notch on the descending part of the tracing, corresponding to aortic valve closure (Fig. 2). With this method, appropriate evaluation of arterial compliance in a given patient is the most problematic issue. Arterial compliance varies with gender, age and the severity

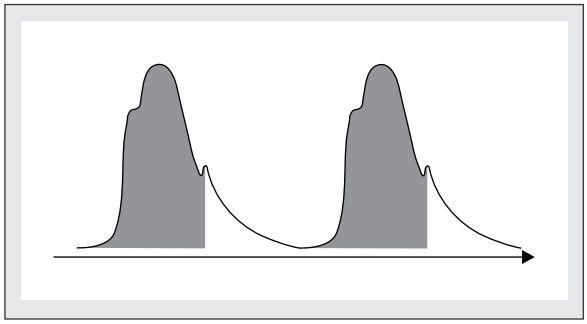

Figure 2. Arterial pressure-based cardiac output (APCO) measurement

of atherosclerotic lesions. The less compliant (more stiff) the arterial system, the lower the dynamics of pressure changes with time. With the same stroke volume, the pressure curve may look different due to a varying pressure increment per unit of time — the curve will be more or less steep. Thus, obtaining true arterial compliance is of major importance for cardiac output measurement based on a pulse wave analysis.

Calibrated methods

These are the most reliable of the APCO methods, as arterial compliance is actually calculated. For this purpose, cardiac output must be independently measured using another method before stroke volume monitoring is initiated. With known cardiac output and other parameters of the pulse wave analysis, the only unknown variable remains arterial compliance. Following such calibration, reliable hemodynamic measurements may performed for several hours. This approach to cardiac output monitoring is usually combined with methods based on transpulmonary indicator dilution, which require the presence of a catheter with a dedicated sensor (temperature or lithium level probe) in the arterial system. Following measurement using the dilution method, the catheter continues to be used for cardiac output measurement using APCO and calculated arterial compliance. Other technique allowing to obtain calibrated

Table 5. Pulse wave analysis

Available technologies → Calibrated methods: pulse wave analysis using an arterial catheter used for transpulmonary dilution methods (PiCCO, VolumeView, LiDCO)/Uncalibrated minimally invasive methods (FlowTrac/Vigileo, Edwards Lifesciences, USA; ProAQT/Pulsioflex, Pulsion, Maquet, USA; LiDCOrapid/PulseCO, LiDCO, United Kingdom)/Uncalibrated completely noninvasive methods (ClearSight, Edwards Lifesciences, USA; T-line system, TL-300, TensysMedical Inc., USA)	
Advantages	Relatively low measurement invasiveness (particularly uncalibrated methods) Rapidly obtained hemodynamic data Beat-to-beat measurement Measurement reproducibility Additional measurements: dynamic parameters — SVV, PPV
Disadvantages	Cardiac output measurement possible only with preserved sinus rhythm Less precise than thermodilution methods Highest precision with calibrated methods, followed by minimally invasive and noninvasive methods Completely noninvasive methods reserved for patients with preserved peripheral circulation and possible only for a limited time Dynamic parameters may be obtained only if the patient is sedated, ventilated with constant tidal volume, with closed chest and no elevation of intra-abdominal pressure
Indications	Patients without cardiac arrhythmia, high risk surgical procedures Method particularly useful in patients under general anaesthesia (muscle relaxation, ventilation) Ventilated patients (if dynamic parameters of intravascular volume are evaluated → SVV/PPV cannot be evaluated after extubation, but continued stroke volume monitoring is still possible and may guide fluid therapy)

SVV — stroke volume variation; PPV — pulse pressure variation

APCO is Oesophageal Doppler described in next chapter. Obtained in that way cardiac output and calculated value of arterial compliance provides calibrated APCO with the use of typical arterial pressure curve.

Uncalibrated methods

These may be categorized into minimally invasive and noninvasive. Both use estimated arterial compliance, calculated using an algorithm based on the patient's anthropometric data, age and gender. With minimally invasive methods, the monitor is attached to a cannula introduced to a peripheral artery (most commonly the radial artery) and patient data are entered into the device. When a pulse wave tracing is obtained, continuous hemodynamic monitoring may begin.

Completely noninvasive pulse wave analysis methods are also available

The most popular device consists of a finger cuff and a plethysmography-based sensor that measures arterial width. With this method, an increasing arterial diameter during systole is recorded. By gradually increasing the pressure in the cuff, a pressure value is identified above which the vessel diameter remains constant, and which corresponds to arterial blood pressure. A blood pressure tracing is thus obtained which is analysed further as in minimally invasive uncalibrated methods. Another method is based on applanation tonometry (T-line system). A pressure sensor is placed over the radial artery and by gradually increasing the pressure, the maximum (systolic) and mean arterial pressure is determined, which yields a blood pressure tracing and allows for calculation of cardiac output.

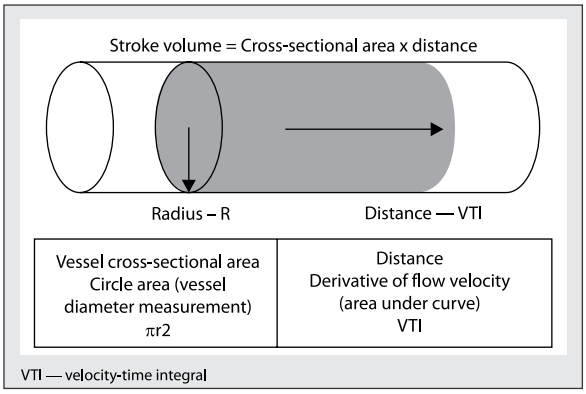

Figure 3. Doppler effect

METHOD #4. DOPPLER EFFECT

Cardiac output may also be evaluated using ultrasound. Following each cardiac contraction, the generated stroke volume travels a certain distance. Theoretically, it has a shape of a cylinder that forms distal to the valve. By knowing the base area and the height of a cylinder, its volume may be calculated. In ultrasound-based methods, vessel diameter is calculated and its cross-sectional area is calculated with an assumption of its circular shape. Using the Doppler effect, local blood velocity is measured which varies during systole. The higher the blood volume ejected in a unit of time through a constant cross-section, the higher the blood velocity and distance travelled. In the Doppler method, this distance is reflected by the velocity-time integral (VTI), or the derivative of velocity with respect to time (area under the velocity/time curve). The product of these two values (cross-sectional area and distance) corresponds to stroke volume (Fig. 3). This approach to stroke volume calculation is based

Table 6. Echocardiography

Available technologies → TTE (many manufacturers)/TOE (multiple-use probes: Philips, the Netherlands; GE, USA/single-use probes: ImaCor, USA)	
Advantages	Completely noninvasive (TTE) or minimally invasive (TEE) Allows evaluation of intravascular volume by measuring respiratory variation of the vena cava inferior Evaluation of a volume parameter: end-diastolic volume
Disadvantages	Imprecision of cardiac output measurement resulting from the need to assume that the shape of the outflow tract is circular and the diameter of the left ventricular outflow tract is constant Measurement of cardiac output is time-consuming Continuous measurement is not possible Requires experience and skills (learning curve) Precision depends on subjectively chosen images
Indications	Comprehensive evaluation of global and regional systolic function, valvular apparatus, presence of pericardial fluid Evaluation of the response to fluid therapy, particularly in conscious patients

TTE — transthoracic echocardiography; TEE — transoesophageal echocardiography

Table 7. Oesophageal Doppler

Available technologies → CardioQ (Deltex, USA); Waki (Atys Medical, France); HemoSonic 100 (Arrow International, USA)	
Advantages	Minimally invasive method Continuous (beat-to-beat) measurement Reproducibility of measurements Additional measurements: changes in preload and afterload may be predicted based on the shape of the flow velocity curve and FTc
Disadvantages	Measurement imprecision, particularly with the presence of a gastric tube Significant cost of a single-use Doppler probe Difficulties with maintaining constant probe position Requires experience and skills (learning curve)
Indications	Unconscious and ventilated patients in whom an unchanged position of the probe may be maintained High-risk surgical procedures

FTc — flow-time corrected

on several simplifications. It is assumed that the cross-section is circular and the generated blood flow is laminar.

Echocardiography: transesophageal (TEE) and transthoracic (TTE)

Measurement of cardiac output is based on the determination of the cross-sectional area (S) and blood flow velocity, usually within the left ventricular outflow tract (VTI) below the aortic valve. The system measures heart rate (HR) and calculates cardiac output using the formula: $CO = S \times VTI \times HR$. Left ventricular cardiac output calculation may be based on the measurement of flow through either the aortic valve (in practice, within the left ventricular outflow tract) or the mitral valve (Table 6).

Oesophageal Doppler

In this method, based on the anatomical proximity of the oesophagus and the descending aorta, a small ultrasound probe is introduced to the oesophagus. Following introduction, the probe is positioned so as to allow the ultrasound beam to cross the aorta. A reading of blood flow is then obtained as a curve which depicts flow velocity changes in respect to time. The distance travelled by blood with each cardiac contraction may be obtained from the area under the curve. Vessel diameter is obtained indirectly, by an estimation based on anthropometric data. The result requires some correction to adjust for blood volume diverted from the aorta to the aortic arch arteries, proximal to the measurement site. This method allows for continuous cardiac output measurement (Table 7).

METHOD #5. CHEST IMPEDANCE MEASUREMENT

This approach is based on measurements of voltage changes when a low-amperage current runs through the chest. According to Ohm's law, the current (I) is the ratio of the voltage (U) to the resistance (R) generated by a conductor: $I = U/R$.

Thus, with a constant current running through a conductor, the voltage depends only on the resistance generated by the conductor. This is the basis for bioimpedance methods used to measure cardiac output. The chest as a conductor is not uniform – various tissues are characterized by different resistance and are poor conductors, except for plasma. When a constant current runs through the chest, the voltage measured at the ends of this system undergoes cyclic changes. This means that the chest, being a conductor, changes its resistance in a cyclic way. The best conductor in this system is plasma, the volume and properties of which change during the cardiac cycle, affecting the overall resistance of the system. Erythrocytes suspended in plasma are characterized by high electrical resistance. During diastole, blood in the aorta does not flow forward and erythrocytes are chaoti-

Table 8. Impedance methods

Available technologies → Bioimpedance (NICCOMO, MedisGmbh, Germany; Physio-Flow, NeuMeDxInc, UK; BioZ, CardioDynamics, USA; NICOMON, Larsen and Toubro Ltd. India; CMS3000, Cheers Sails Medical, China)/Bioreactance (CHEETAH-NICOM, Newton Center, USA)/ Electrical cardiometry (Aesculon/ICON Osypka Medical GmbH, Germany)	
Advantages	Noninvasive method Continuous (beat-to-beat) measurement Reproducibility of measurements Additional measurements: indirect evaluation of thoracic fluid content (TFC)
Disadvantages	Low agreement with reference methods Multiple factors limiting use of this method: cardiac arrhythmia, valvular heart disease, obesity, chest drainage, pleural effusion, subcutaneous emphysema, pulmonary oedema, increased sweating Measurement sensitive to changes in the lead position Interference with other devices (electrocautery) Calculation of the amount of electrically reactive tissue based on biometric data is needed
Indications	Patients in the post-anaesthesia care unit Evaluation of temporal trends Patients treated with continuous renal replacement therapy

cally arranged, which increases the electrical resistance of the blood. During systole, blood is ejected to the aorta and pulmonary arteries, increasing the volume of plasma which is a good conductor. In addition, blood flow forces parallel, linear arrangement of erythrocytes which increases the electrical conductance of plasma. Three modifications of this method are available.

Bioimpedance

This method measures the voltage of the current running through the chest, which increases during systole. According to Ohm's law, this is associated with a decrease in resistance.

Bioreactance

This modification uses an alternating current. Monitored parameters include not only resistance but also the phase shift of the alternating current. The latter depends nearly exclusively on the pulsatile blood flow and is more related to aortic flow, which reduces measurement artifacts.

Electrical cardiometry

This model of bioimpedance signal interpretation is based on the measurement of blood velocity changes which are associated with rapid changes in aortic blood conductance.

All methods based on electrical current measurement only require placing ECG leads in four locations — on both sides of the neck and on lateral chest surfaces. A low-amperage current runs through the chest organs and changes in the impedance or duration of current flow, resulting from the systolic fluctuations described above, are recorded. Stroke volume is calculated based on tracings that depict these changes (Table 8).

CARDIAC OUTPUT MEASUREMENT METHODS AND DETERMINATION OF VASCULAR RESISTANCE

The degree of vasoconstriction is one of the most important hemodynamic parameters. Resistance is a parameter calculated based on the knowledge of pressures and cardiac output. Vascular resistance is the term used to describe total resistance to blood flow in the vascular system, which is a sum of all peripheral resistances. Peripheral resistance is determined by three factors: vessel diameter, vessel length and blood viscosity.

Resistance is calculated using the formula:

$R = \Delta P/Q$,

Where ΔP is the pressure gradient between the beginning and the end of the studied circuit, and Q is blood flow through the circuit, or cardiac output.

In the systemic circulation, systemic vascular resistance (SVR) is derived from the difference between the mean pressure in the aorta (mean arterial pressure, MAP) and the right atrium (central venous pressure, CVP) according to the equation: SVR = (MAP – CVP) / CO. This parameter may be obtained using each of the above described cardiac output measurement methods if central venous pressure is also measured, which requires placement of a central venous catheter and increases the invasiveness of monitoring. Evaluation of SVR is of major importance in patients treated with vasoactive drugs, including patients with sepsis and those with heart failure.

Pulmonary vascular resistance (PVR) is derived from the difference between the mean pressure in the pulmonary artery (pulmonary artery pressure, PAP) and the left atrium (pulmonary capillary wedge pressure, PCWP) according to the equation: PVR = (PAP – PCWP)/CO. This parameter may only be obtained after a Swan-Ganz catheter is placed in the pulmonary artery.

CARDIAC OUTPUT MEASUREMENT METHODS AND EVALUATION OF INTRAVASCULAR VOLUME

Appropriate intravenous fluid therapy is a necessary element of goal-oriented therapy to preserve the body's physiological functions and replace fluid and elec-

trolyte losses in the pre- and intraoperative period due to fasting, perspiration, intestinal preparation, bleeding, etc. [6–8]. Thus, adequate evaluation of volaemia becomes a particularly important goal for cardiovascular stabilization. According to the Frank-Starling law, stroke volume increases with increasing end-diastolic volume until a certain maximum value is reached. Above this threshold, a further increase in end-diastolic volume does not lead to a further increase in cardiac output, while continuation of fluid therapy results in oedema and predisposes one to postoperative complications. The situation is much more difficult in patients with heart failure (Fig. 4). The choice of therapy must take into account both cardiovascular system status and current hemodynamic status. With a stable cardiovascular system (normal peripheral perfusion), the maintenance infusion dose should not exceed 1–2 mL $kg^{-1}h^{-1}$. For the evaluation of intravascular volume, the most useful parameter should permit early and precise determination whether further fluid therapy will lead to an increase in stroke volume. Evaluation of the patient's current cardiac performance expressed as a point on the Frank-Starling curve is thus the basis for successful fluid therapy.

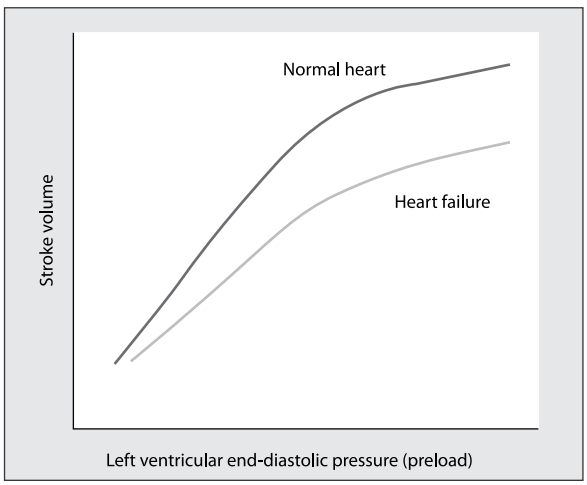

Figure 4. Relation between stroke volume and preload

If fluid therapy results in a significant increase in stroke volume (i.e., by more than 10%), then intravascular volume is suboptimal and may be increased further. These patients are considered fluid responders. Thus, compared to static parameters which are indirect measures of the end-diastolic ventricular volume, dynamic parameters (Table 9) are more useful and reliable for the evaluation of intravascular volume in clinical practice.

Static parameters:

a) Pressure parameters: CVP, PCWP — of questionable clinical utility in current practice;
b) Volume parameters: left ventricular end-diastolic volume (LVEDV) evaluated by echocardiography and global end-diastolic volume index (GEDVI) evaluated by transpulmonary thermodilution.

The normal ranges of these parameters show significant individual variation and are not useful for predicting cardiovascular system response to further fluid therapy.

Dynamic parameters:

a) Evaluation of stroke volume response (increase or no increase) to a therapeutic manoeuvre (when using ultrasound, VTI increment may be evaluated as the remaining parameters required for measuring CO, such as the cross-sectional area at the measurement site, remain constant for a given patient):
— passive leg raising (PLR) — a simple reversible manoeuvre imitating rapid fluid infusion, which transiently and reversibly increases venous return by inducing a fluid shift from the lower limbs and the abdominal reservoir to the chest cavity;
— fluid challenge – infusion of a small fluid volume (approx. 250 mL) during a short time.

Table 9. Methods for the identification of fluid responders

Parameter	Technology	Description	Threshold value	Limitations
Passive leg raising (ΔSV)	Any method measuring SV	Raising lower limbs at 45° for 2–3 minutes + evaluation of SV increase	ΔSV >10%	Possibility to raise legs
SVV/PPV	APCO (pulse wave analysis)	Pressure or SV variation during the respiratory cycle	SVV/PPV >10%	Sinus rhythm, mechanical ventilation at V_T of 8 mL kg^{-1}, sedation Closed chest
Respiratory IVC variation	Ultrasound	Evaluation of the diameter and respiratory variation of IVC	IVC < 1.5 cm Diameter change by > 50%	Continuous measurement not possible Access to the chest Operator skills
Fluid challenge (ΔSV)	Any method measuring SV	Infusion of a small fluid volume during a short time + evaluation of SV increase	ΔSV >10%	Need for actual fluid challenge

V_T — tidal volume; other abbreviations are explained in the text

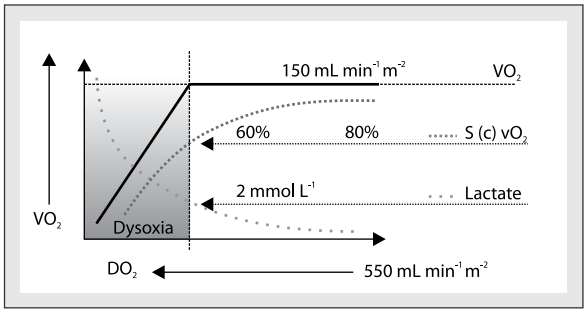

Figure 5. The relationship between oxygen delivery and lactate level and SvO_2

b) Evaluation of pressure or volume variation during the respiratory cycle in a patient on positive pressure ventilation with a tidal volume of 8 mL kg^{-1}:
— pulse pressure variation (PPV),
— stroke volume variation (SVV);
c) Respiratory variation of the inferior vena cava (IVC) diameter. Measurements are made by ultrasound (echocardiography) in the substernal view. With normal intravascular volume, the IVC is wide and does not show respiratory variation.

MICROCIRCULATION MONITORING METHODS — TISSUE PERFUSION PARAMETERS

The methods described above allow for the evaluation of global oxygen delivery (DO_2). This parameter is determined by cardiac output, haemoglobin levels and oxygen saturation. Provision of an adequate blood flow in the macrocirculation is only an indirect treatment goal. The most important goal is effective oxygen and nutrient delivery to cells, i.e., effective gas exchange and respiration at the mitochondrial level. Optimisation of bloodstream parameters must be based on the evaluation of the microcirculation status [9–13], and thus evaluation of the microcirculation remains the primary therapeutic goal. This has led to a search for methods to evaluate the oxygen status, which may answer the question whether further cardiovascular optimisation is necessary, or may identify clinical conditions in which the tissue oxygen debt is not reduced, despite appropriate macrocirculation parameters (Fig. 5).

Oxygen delivery (DO_2) = CO × (1.34 × Hb × SaO_2) + (0.003 × PaO_2)

where SvO_2 — mixed venous blood oxygen saturation.

MICROCIRCULATION MONITORING METHODS

LACTATE LEVEL MEASUREMENT

In physiological conditions, lactate is generated during glucose oxidation. Under aerobic metabolism, lactate is further metabolized to citric acid, and ultimately to carbon dioxide and water. In anaerobic conditions, lactate tissue metabolism is inhibited which is manifested with an increased serum lactate level. Lactic acid is then only used for gluconeogenesis in the liver, resulting in glucose synthesis. Lactate levels above 2 mmol L^{-1} are a warning sign that may indicate tissue oxygen deficit. With lactate level monitoring, the effectiveness of the instituted therapy may be evaluated. Physiologically, the lactate level is reduced by approx. 10% per hour although lactate elimination is slower in patients with hepatic dysfunction.

EVALUATION OF VENOUS BLOOD OXYGEN SATURATION

Mixed venous blood oxygen saturation (SvO_2 — pulmonary artery) or central venous blood oxygen saturation ($ScvO_2$ — vena cava superior) are parameters that provide information about the ratio of tissue oxygen delivery to tissue oxygen uptake. With DO_2 reduction, oxygen extraction from haemoglobin becomes increased, initially preventing hypoxia. Only after this mechanism is fully saturated, oxygen debt begins to rise and anaerobic metabolism prevails at the tissue level. A drop in venous oxygen saturation (SvO_2 < 70% or $ScvO_2$ < 65%) indicates increased oxygen extraction from haemoglobin, which is a measure of increased tissue oxygen demand. Factors that determine venous oxygen saturation include the following: the haemoglobin (Hb) level; the degree of haemoglobin saturation with oxygen or arterial oxygen saturation (SaO_2); cardiac output (CO); and tissue oxygen uptake (VO_2). Provided that Hb, SaO_2, and VO_2 are momentarily constant, SvO_2 reflects cardiac output changes. Monitoring of this parameter allows for the relatively rapid evaluation of global tissue oxygen delivery. In most cases, its rapid reduction indicates inadequate tissue oxygenation (progressive shock) and requires prompt therapeutic measures. This is one of the more important parameters of tissue oxygenation which may constitute a major therapeutic target in the perioperative period. Venous oxygen saturation may be continuously monitored using an optic fibre integrated with a dedicated catheter, which clearly facilitates rapid management decisions in the setting of continuous changes in cardiovascular dynamics during surgery. Venous oxygen saturation is a parameter that describes global changes in tissue oxygenation. In cases of local hypoxia which may also develop during major surgery, this method may yield false positive results. Similarly, measurements may be falsified by a block of oxygen release from haemoglobin at the microcirculation level, which may occur in some intoxications, e.g., with cyanate, and in sepsis.

MEASUREMENT OF PCO_2 GAP

The difference in the partial pressure of carbon dioxide between the arterial and the venous blood (veno-arterial pCO_2 difference, Pcv-aCO_2) is physiologically constant and should not be higher than 5 mmHg. Monitoring of this parameter may be an excellent addition to the valuation of venous blood oxygen saturation in order to identify pa-

tients with hypoperfusion in whom venous blood oxygen saturation is falsely elevated (i.e., > 70%). An increase in the veno-arterial pCO_2 difference is mostly likely caused by tissue carbon dioxide retention due to a reduction in cardiac output and blood flow in the microcirculation. The pCO_2 gap increases even if peripheral tissue oxygen uptake is not increased due to a pathological process despite actual ischemia (diffusion abnormalities, mitochondrial damage). In such a situation, oxygen extraction from the erythrocyte does not increase while venous blood oxygen saturation will not change despite ischemia at the microcirculation level. Thus, the combination of SvO_2 < 70% ($ScvO_2$ < 65%) and Pcv-aCO_2 > 5 mmHg allows for better identification of abnormal oxygen delivery and uptake. In addition, the response of venous blood oxygen saturation and the pCO_2 gap to effective treatment is more rapid compared to changes in lactate level, as the normalization of these parameters occurs almost immediately following improved perfusion.

Measurement of tissue saturation

An even more direct approach to monitor tissue oxygenation is evaluation of tissue saturation using near-infrared spectroscopy (NIRS). This is a completely noninvasive method which only requires that dedicated source and detector probes (optodes) containing infrared-emitting diodes and detectors recording the reflected light are placed on the skin surface. The NIRS signal penetrates tissues immediately adjacent to the sensor and allows measuring blood oxygen saturation in the microcirculation. Although the principle underlying this method is similar to pulse oximetry, the latter analyses only the signal in the systolic phase, which allows measuring arterial blood oxygen saturation, while in NIRS, saturation is measured continuously, as well as in the veins and capillaries. Thus, saturation may be measured in all conditions, also when tissue perfusion is reduced. This permits rapid identification of ischemia and the evaluation of the treatment effectiveness. Currently, this technique is mostly used in the operating room in order to evaluate microcirculation in the frontal cortex (primarily in neurosurgery and cardiac surgery). In children, low subcutaneous fat content allows for the evaluation of tissue oxygen saturation within abdominal organs by placing NIRS electrodes in the prerenal area.

PATIENT SELECTION — CHOICE OF THE HEMODYNAMIC MONITORING METHOD

Stability of the cardiovascular system depends on many interrelated variables. Proper diagnosis and the institution of adequate treatment require evaluation of several parameters. No single isolated parameter, even one as important as cardiac output, is sufficient. Cardiac output is determined by not only myocardial contractility but also by adequate intravascular volume which, in turn, depends on both the absolute volume of circulating blood and the vascular tone. Tools for cardiovascular monitoring should be diversified and adjusted to the clinical scenario.

TYPES OF HEMODYNAMIC MONITORING

BASIC MONITORING

Basic parameters should include continuous ECG monitoring (leads II and V5), arterial oxygen saturation (SaO_2) and indirect (noninvasive) blood pressure measurements. These should be combined with clinical observation for possible tissue perfusion disturbances (capillary refill). This approach is appropriate in patients without an increased surgical risk, i.e., with normal physiological reserves that allow the compensation of increased oxygen demand. This type of monitoring should be used in patients undergoing low- to moderate-risk surgical procedures, and may also be a basis for extended hemodynamic monitoring.

EXTENDED MONITORING

This approach also includes evaluation of the intravascular volume using a set of tools that may identify fluid responders by measuring static parameters, i.e., change in stroke volume (ΔSV) and/or dynamic parameters (SVV/PPV). This usually requires placing an arterial cannula (APCO methods) or the use of an ultrasound probe (echocardiography, Doppler methods). In most patients, this monitoring should allow the appropriate choice of inotropic and vasoactive agents in order to optimize cardiac preload, myocardial contractility and afterload.

ADVANCED MONITORING

In order to obtain a complete set of parameters needed to evaluate cardiovascular function, extended monitoring should be combined with a central venous and/or pulmonary artery catheter, which allows measuring systemic and/or pulmonary vascular resistance (SVR/PVR). This approach also involves using such tools as the Swan-Ganz catheter and transpulmonary thermodilution methods. Advanced monitoring allows one to obtain a comprehensive set of parameters describing cardiovascular dynamics, which is particularly important in fluid non-responders and patients who require vasoactive or inotropic agents. Advanced hemodynamic monitoring permits evaluation of venous blood oxygen saturation and the pCO_2 gap. Both these parameters are most useful in ICU patients and during a narrow range of specialist procedures.

For hemodynamic monitoring during anaesthesia, continuous data acquisition is of particular importance, as it allows for immediate therapeutic interventions in the setting of dynamic cardiovascular changes during surgery. Thus, monitoring usually begins with a pulse wave

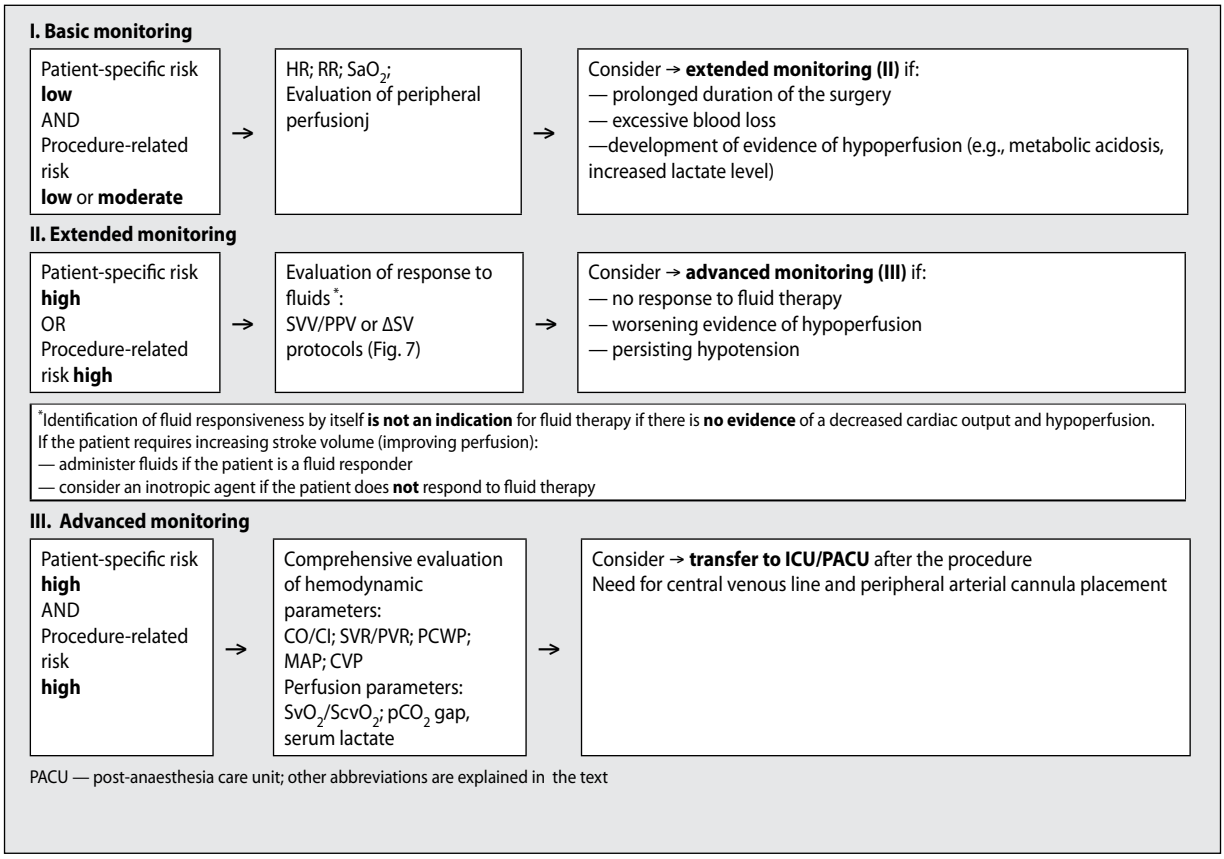

Figure 6. Choice of the monitoring method

analysis or Doppler methods (extended monitoring). More comprehensive evaluation of the cardiovascular function is possible with central venous cannulation (advanced monitoring). Thus, the knowledge of particular types of monitoring and the options of extending it allows for the adequate adjustment of method selection to specific clinical settings, resulting from both the patient's condition (vascular access, cardiac arrhythmia, valvular heart disease) and the procedural details (thoracotomy, atypical patient position).

CHOICE OF THE MONITORING METHOD (FIG. 6)

I. In patients at low individual risk undergoing low- to moderate risk surgery, basic monitoring seems sufficient as the initial approach. Extended monitoring should be initiated in cases where there is evidence of peripheral hypoperfusion (metabolic acidosis, increased serum lactate level, perfusion disturbances), increasing duration of surgery, or excessive blood loss.

II. With the presence of high risk in one category (patient/surgery), extended monitoring is warranted as the initial approach.

Advanced monitoring should be initiated in cases with no response to fluid therapy, development or worsening of the evidence of peripheral hypoperfusion, or persisting hypotension.

Attention: identification of fluid responsiveness by itself is not an indication for fluid therapy if there is no evidence of a decreased cardiac output and hypoperfusion. Firstly, it should be determined whether the patient requires an improving/increasing stroke volume. If the patient requires active treatment and responds to fluids, this therapy should be instituted immediately. If the patient requires active treatment but does not respond to fluids, the first option should be drug therapy (inotropic and vasoactive agents) (Fig. 7).

III. With the presence of high risk in each category (patient/surgery), advanced monitoring is warranted as the initial approach.

This requires at least arterial and central venous cannulation in order to allow the comprehensive evaluation of hemodynamic parameters and tissue perfusion (microcirculation).

It should be noted that a parametric evaluation of the patient's risk should not replace a clinical evaluation. Scores are only additional tools. The most important aspect is conducting an attempt to answer the question regarding physiological reserves in a given patient, as this factor is the major determinant of intraoperative monitoring and management [14].

Algorithm describing perioperative haemodynamic optimisation in patients undergoing non-cardiac surgery is depicted in Figure 7.

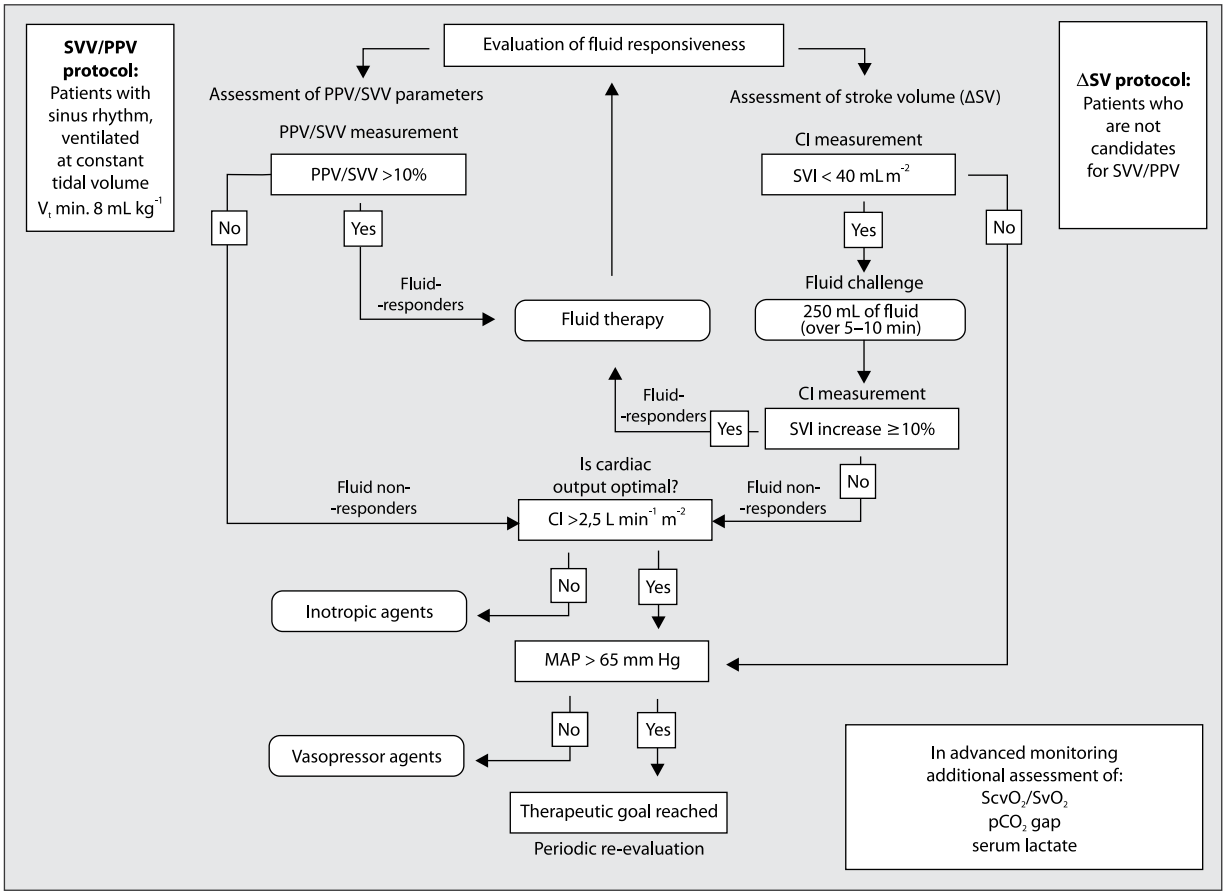

Figure 7. Algorithm describing perioperative haemodynamic optimisation in patients undergoing non-cardiac surgery

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