Interpretation of blood pressure signal: physiological bases, clinical relevance, and objectives during shock states

Abstract

Achievement of a mean blood pressure (MBP) target is one of the hemodynamic goals to ensure an adequate blood perfusion pressure in critically ill patients. Arterial catheter allows for a continuous and precise monitoring of arterial pressure signal. In addition to giving a precise MBP monitoring, analysis of the blood pressure wave provides information that may help the clinician to interpret hemodynamic status. The interpretation of BP wave requires the understanding of simple principles. In this review, we first discuss the physiological mechanism responsible for arterial pressure generation. We then emphasize the interpretation of the static indexes and the dynamic indexes generated by heart-lung interactions derived from arterial pressure wave. Finally, we focus on MBP value as a therapeutic target in critically ill patients. We discuss the recommended target MBP value by reviewing available data from experimental and clinical studies.

Keywords

Mean blood pressure · Arterial pressure · Hemodynamics · Septic shock

Abbreviations

ARDS Acute respiratory distress syndrome
BP Blood pressure
C Compliance
CO Cardiac output
DBP Diastolic blood pressure
HR Heart rate
LV Left ventricle
MBP Mean blood pressure
PEEP Positive end-expiratory pressure
PP Pulse pressure
RV Right ventricle
SBP Systolic blood pressure
SV Stroke volume
SVR Systemic vascular resistance
RAP Right atrial pressure

Introduction

The blood pressure (BP) signal provides information, which aids the physician in assessing the patient’s hemodynamic status, and guides treatment. Interpreting the BP wave requires the understanding of simple principles. In this review, we summarize these physiological principles; we then detail the information provided by the indexes obtained from BP curve analysis and their clinical contribution. Lastly, we focus on mean blood pressure (MBP) as a therapeutic objective in critically ill patients, and the MBP target to be reached during septic shock.
Fundamental bases and hemodynamic principles

The BP signal fluctuates around a mean value according to a complex mechanism. From this value, BP reaches systolic blood pressure (SBP), and diastolic blood pressure (DBP). The difference between both values is the arterial pulse pressure (PP; \( PP = SBP - DBP \)). The BP signal undergoes changes along its course from the proximal aorta (aortic pressure) to the peripheral arteries (peripheral blood pressure) that may be modeled by wave reflection and pulse wave amplification phenomena.

The arterial system may be considered as a functional unit interposed between the left ventricle (LV) and the capillary exchange and is divided into two subunits, namely the large arteries (characterized by their capacitive function) and the distal arterioles (characterized by high resistance). These features enable the transformation of the pulsatile flow into a continuous flow.

The major hemodynamic principles are derived from the dynamics of a Newtonian fluid (water) circulating continuously in rigid tubes. Neither conditions are met in physiology where the assumptions are that the flow is described by linear equations and that the pressure/flow relationship obeys Ohm’s law.

Continuous flow hemodynamics

In this model, cardiac output (CO) is considered continuous rather than pulsatile. MBP would be the pressure required to obtain an identical CO in the absence of pulsatility.

Hydrostatic and hydrodynamic pressures

Pascal’s first principle of fluid pressure establishes that below the fluid surface there is a hydrostatic pressure. Similarly, blood exerts hydrostatic pressure on vascular wall, called mean systemic filling pressure, which would be observed under no-flow conditions. Blood is a moving fluid which exerts additional pressure (hydrodynamic pressure). This moving pressure, called MBP, is generated by cardiac activity.

Resistance

Resistance is the frictional force opposing blood flow. If blood is assimilated to a Newtonian fluid under of a laminar regimen, Hagen and Poiseuille’s law may be applied to blood circulation:

\[
R(SVR) = \frac{8L\mu}{\pi r^4}
\]

Systemic vascular resistances (SVR) are directly proportional to blood vessel length (\( L \)) and blood viscosity, and varies inversely with mean blood vessel radius (\( r \)). As shown by this relationship, the radius plays a predominant role in vascular resistance. Therefore, because of their large diameter, the large capacitance vessels (aorta and peripheral arteries) provide little flow resistance. Conversely, a minor change in arteriolar radius leads to a significant variation in resistance.

Darcy’s law

Darcy’s law establishes the relationship between flow (\( Q \)), pressure gradient (\( P_1 - P_2 \)), and resistance (\( R \)):

\[
Q = C \times (P_1 - P_2) = \frac{1}{R} \times (P_1 - P_2)
\]

Flow is linearly proportional to the pressure difference. \( C \) is the hydraulic conductance of fluid, and hydraulic resistance (\( C = 1/R \)) is its opposite. Poiseuille’s law can be expressed as follows:

\[
Q = \frac{\pi r^4}{8L\mu} \times \Delta P
\]

Application to hemodynamics

Applying Darcy’s law to blood circulation leads to the key relationship governing hemodynamics:

\[
CO = \frac{(MBP - RAP)}{SVR}
\]

MBP may be expressed by the following equation:

\[
MBP = CO \times SVR + RAP = (HR \times SV) \times SVR + RAP
\]

in which HR represents the heart rate; SV, the stroke volume; and RAP, the right atrial pressure. Based on the hypothesis that the RAP is negligible, the relationship is simplified as follows:

\[
MBP = CO \times SVR = (HR \times SV) \times SVR
\]

MBP’s determinants are CO and SVR. This relationship shows that for a given MBP value, CO depends largely on SVR, regardless of how it is generated (high HR/low SV or low HR/high SV). SVR is the “reactive variable”: whereas in low SVR states (i.e., septic shock) SVR drives the equation with CO limiting, this contrasts with cardiogenic shock where elevated SVR is a reaction to the low CO. Furthermore, this equation provides a good illustration of the impact of the treatments used in patients presenting shock. Such treatments are aimed at increasing MBP, either by enhancing CO (volume administration and positive inotropic agents), or increasing SVR (vasoressor amines). Hemodynamic principles are based on
the study of a Newtonian fluid circulation in rigid tubes under laminar conditions. As blood is not a perfect fluid, and as CO is generated in a pulsatile mode, some of these laws must be adapted to the cardiovascular system’s specific features, and lead us to consider pulsatile flow hemodynamics.

Pulsatile flow hemodynamics

As cardiac activity is biphasic, blood flow and hydrodynamic pressure vary when the LV is in systole (increased velocity and pressure) or diastole (decreased velocity and pressure). Thus, BP fluctuates between a maximum (SBP) and a minimum (DBP). The degree of these fluctuations, reflected by the pulse pressure (PP), depends on ventricular ejection volume and rate, peripheral resistances, and arterial walls’ viscoelastic properties.

Compliance

The aorta is capable of absorbing part of the SV during ventricular systole, releasing it during diastole. This property is linked to its elasticity, known as compliance, and allows for the offset of systolic ejection, thereby limiting BP elevation and converting pulsatile flow into continuous peripheral flow. The Windkessel simplified model may be applied to the aorta [1] and the overall compliance (C) may be estimated by using the following formula:

\[ C = \frac{SV}{\text{aorticPP}} \]

Reflected waves and amplification of the pulse wave

Aortic pressure may be modeled as the summation of incident BP and reflected waves. The incident BP wave propagates distally from the proximal aorta at high velocity (8–10 m s\(^{-1}\)). On its path, it encounters arterial bifurcations and arteriolar blocks, resulting in reflected waves, which are added to the incident wave at the aortic root during diastole. This phenomenon is responsible for coronary perfusion, which mainly occurs during diastole. In specific pathological conditions with decreased vascular compliance (hypertension and the elderly), the velocity of the incident and reflected wave is greater and instead of adding to the diastolic part of the aortic BP wave, it adds to its systolic part, resulting in aortic SBP increase [2]. The same phenomenon may be observed in subjects of short height because of a shortened return of the reflected wave. The addition occurs at the systolic time instead of the diastolic time, increasing the aortic SBP with its deleterious consequences (increased risk of stroke, increased left ventricular afterload) and decreasing the coronary perfusion pressure.

Pulse wave amplification reflects the BP increase measured peripherally, as compared to the aortic level. SBP and PP mainly increase peripherally, leading to a central SBP and PP overestimation of approximately 15 mmHg. This phenomenon is primarily accounted for by increasing differences in arterial caliber and compliance, from the center towards the periphery [3]. Although this amplification is more pronounced in young male subjects and in cases of vasodilation (high compliance), it tends to fade in elderly subjects, hypertensive patients, and in cases of vasoconstriction [4, 5].

Pulse wave amplification has little effect on MBP and DBP, which both tend to remain constant from the aorta to the periphery [3].

Data obtained from blood pressure signal analysis in intensive care units

BP curve analysis provides three types of data on the patient’s hemodynamic status. The first approach relies on the interpretation of BP static indices (MBP, SBP, DBP, and PP). The second approach relies on the analysis of BP variations induced by applying positive inspiratory pressure which is aimed at predicting hemodynamic effects of volume loading. The third approach is the mathematical analysis of the pulse wave shape.

Static indexes

Mean blood pressure

Measurement methods for MBP. Intensive care monitors measure MBP by calculating the integral of the BP wave (area under the curve). MBP may also be estimated from SBP and DBP by using the following formula:

\[ \text{MBP} = \frac{2}{3}\text{DBP} + \frac{1}{3}\text{SBP} = \text{DBP} + \frac{1}{3}(\text{SBP} - \text{DBP}) = \text{DBP} + \frac{1}{3}\text{PP} \]

DBP contributes twice as much to MBP as SBP. This formula was shown to provide an accurate MBP assessment in critically ill patients [6].

MBP determinants and informative value. The determinants of MBP are CO, SVR, and mean systemic filling pressure, which is assumed to be equal to RAP in clinical practice. In intensive care patients, isolated or combined failure of one of these factors may result in an MBP decrease when physiological compensation mechanisms are overwhelmed. Thus, an MBP decrease may be accounted for by either a decrease in CO, insufficiently compensated by increased vascular peripheral resistances, or by inadequate vasodilation along with insufficient
cardiac compensation. Analysis of MBP separately does not allow for determining the mechanisms responsible for shock.

Two pathological situations may lead to an erroneous MBP interpretation. The first condition is related to high extravascular pressure, responsible for decreased perfusion pressure of the peripheral organ. This is observed in cases of intracranial hypertension, intra-abdominal hypertension, and compartment syndrome. The second is seen in right heart diseases, which are associated with significant RAP elevation, which can no longer be ignored in the MBP equation ($\text{MBP} = (\text{CO} \times \text{SVR}) + \text{RAP}$). In such cases, observed MBP underestimates the true perfusion pressure.

**Diastolic, pulsed, and systolic blood pressures**

In healthy subjects, DBP remains nearly constant from the aorta to the peripheral arteries. Its main determinant is vascular tone. Thus, a low vascular tone (sepsis, vasodilators) is responsible for a drop in DBP. The DBP also depends on the duration of the diastole and BP decay time constant. A short diastole (tachycardia) is associated with high DBP, whereas a prolonged diastole (bradycardia) is associated with low DBP. If we assume that BP decreases monoexponentially during diastole, it has a time constant ($\text{Tau}$) which is equal to the product of SVR multiplied by compliance. Tau shortening is associated with a decrease in DBP, which is related to either decreased resistances (vasomotor tone decrease), or decreased arterial compliance. In summary, low DBP is observed in cases of vasodilatation, bradycardia, or decreased arterial compliance.

The PP is determined by SV and compliance of large arteries ($\text{PP} = \text{SV}/C$). A decrease in SV is associated with decreased PP, whereas a decrease in compliance is associated with increased PP. The decrease in vascular compliance with age causes a decrease in DBP along with an increase in PP and SBP [7]. Thus, detecting a lowered PP in the elderly is indicative of a decrease in stroke volume. The main determinants for SBP are SV, arterial compliance, and SVR. SBP is physiologically an essential determinant of LV afterload. In some cases, the combined analysis of various BP indexes (MBP, PP, SBP, and DBP) and patient characteristics (age and cardiovascular disease) may allow for a precise assessment of hemodynamic status. For instance, an elderly patient presenting a DBP of 60 mmHg and SBP of 80 mmHg (MBP 66 mmHg) is likely to experience a decreased SV, as PP is lowered to 20 mmHg. If SV was normal, PP would have been close to 60 or 70 mmHg, i.e., enlarged, because of age-related decreased arterial compliance. In such a patient with low PP, hypovolemia or cardiac failure must be considered, potentially requiring volume administration or positive inotropic agents, depending on the clinical context.

Dynamic indexes of preload-dependence, derived from the blood pressure curve

The analysis of short-term variations in BP related to positive pressure ventilation allows for the assessment of existing preload-dependence. This dynamic approach is aimed at selecting those patients who would respond to volume expansion.

**Physiological bases**

The Frank–Starling relationship describes SV variation depending on ventricular preload [8]. In healthy subjects, this relationship is curvilinear, and the ventricles function on the ascending part of the curve to such a degree that a preload increase is associated with significantly increased SV and thus increased CO (preload reserve). In acute cases, a preload increase may not lead to increased SV, either because the ventricles function on the flat part of the Frank–Starling curve, or because the preload/SV relationship is modified (heart failure), which is referred to as preload-independence, and in which fluid challenge might be deleterious.

Cyclic variations in alveolar pressures induced by mechanical ventilation are responsible for modifications in ventricular preload and afterload. Upon insufflations, the increase in intrathoracic and transpulmonary pressures (alveolar pressure–pleural pressure) causes a decrease in right ventricular (RV) preload, an increase in RV afterload, and increased LV preload. The SV of the right ventricle is thus decreased during insufflations, which is responsible for a decrease in left ventricular (LV) preload and in its SV, two to four systoles later. The more the LV is on the initial part of the Frank–Starling relationship (preload-dependence), the more the decrease in SV is pronounced. As SV is a determinant of BP, its variations induce modifications of the BP wave.

**Respiratory variation in systolic blood pressure: delta SBP and delta down**

$\Delta\text{SBP}$ is the difference between maximum and minimal SBP during a respiratory cycle. $\Delta\text{SBP}$ was broken down into two other indexes: delta up ($\Delta\text{up}$) and delta down ($\Delta\text{down}$). The measurement of these two indexes is performed with reference to the SBP measured during an
end-expiratory pause (SBPref). $\Delta_{\text{down}}$ is the difference between SBPref and the lowest value obtained during the respiratory cycle. $\Delta_{\text{down}}$ illustrates the decrease in LV preload and SV during expiration as an out-of-phase response to the RV decrease in SV occurring during insufflation (Fig. 1).

The clinical relevance of $\Delta_{\text{SBP}}$ and $\Delta_{\text{down}}$ as predictors of preload-dependence was validated in a study by Tavernier et al. involving septic shock patients [9]. In that study $\Delta_{\text{SBP}} \geq 10$ mmHg and $\Delta_{\text{down}} \geq 5$ mmHg were predictors of an SV increase of at least 15% in response to fluid administration, with excellent positive and negative predictive values (>90%).

**Respiratory variation in pulse pressure: delta PP**

The PP is determined by SV and arterial compliance. Considering the absence of significant changes in arterial compliance over the respiratory cycle, it has been assumed that the respiratory variability of PP should accurately predict fluid responsiveness [10]. In the study by Michard et al. [11], conducted on 40 mechanically ventilated septic shock patients, a high delta PP ($\Delta_{\text{PP}} > 13\%$) enabled the differentiation between responders and non-responders to volume expansion (increase in cardiac index of >15%), with a 94% sensitivity and a 96% specificity. Subsequently, these results were confirmed by numerous other studies [12, 13]. Similarly to $\Delta_{\text{down}}$, baseline $\Delta_{\text{PP}}$ correlates with the degree of response to volume administration. Furthermore, $\Delta_{\text{PP}}$ analysis would allow the prediction of the hemodynamic effects secondary to an increase in positive end-expiratory pressure (PEEP). It was shown that the higher $\Delta_{\text{PP}}$ at the zero PEEP, the higher the decrease in cardiac output induced by application of PEEP in patients with acute respiratory distress syndrome (ARDS) [14].

**Limits of dynamic indexes**

Dynamic indexes have been validated in mechanically ventilated and sedated patients, without spontaneous breathing, presenting regular cardiac rhythm. These indexes cannot be used in patients with arrhythmia. In patients with spontaneous respiration, the specificity of $\Delta_{\text{PP}}$ is low [15]. A recent study [16] suggests that, in mechanically ventilated patients with spontaneous breathing, the elevation of PP by more than 5 mmHg at the end of a 15-s end-expiratory pause could be useful (sensitivity 87%, specificity 100%) to predict a beneficial effect of fluid infusion. The relevance of respiratory BP variations also depends on the tidal volume. In the studies that have validated these indexes, tidal volumes were greater than 8 mL/kg of predicted weight. The use of low tidal volumes during ARDS diminishes their sensitivity [17]. However, as a result of decreased pulmonary compliance, marked cyclic variations in alveolar pressure are likely to occur during ARDS, generating marked cyclic variations in transpulmonary pressure and intrathoracic pressure, even in the case of low tidal volume [18]. In this regard, the study by Huang et al. suggests that $\Delta_{\text{PP}}$ remains a
valid preload-responsiveness index (sensitivity 70%,
specificity 100%) in ARDS patients ventilated with low
tidal volumes (6.4 mL/kg) and high positive expiratory
pressures (13.9 cmH₂O) [19].

Information provided by the analysis of the arterial
pressure waveform

Please refer to the electronic supplementary information.

**What is the target blood pressure in septic shock
states?**

Initial treatment of hemodynamic failure during septic
shock mainly relies on volemic optimization and admin-
istration of vasoconstrictors such as norepinephrine. In
healthy subjects, organ perfusion remains stable because
of self-regulatory mechanisms for MBPs ranging from 60
to 100 mmHg. When MBP drops below 60–65 mmHg,
perfusion becomes dependent on the MBP level (“critical
MBP”), decreasing linearly with MBP [20].

According to the Surviving Sepsis Campaign guide-
lines, MBP should be elevated to at least 65 mmHg in
order to avoid organ hypoperfusion in patients with septic
shock [21]. Nevertheless, these recommendations neither
define a target MBP level, nor propose a precise MBP
objective to be reached in function of patient’s charac-
teristics (age and cardiovascular diseases). During septic
shock, vasomotor and microcirculation disorders might
upregulate self-regulatory thresholds towards higher MBP
values [22], which would require MBP levels greater than
65 mmHg to ensure sufficient tissue perfusion pressure.

Following volume status optimization, norepinephrine
is the most commonly used vasopressor to increase MBP,
which relies on strong experimental and clinical argu-
ments. Optimal dosage and treatment objectives in terms of
target MBP levels are, however, poorly assessed, and
remain controversial.

Scientific literature is scarce and contradictory with
regard to the dose-dependent effects of catecholamines
and the optimal MBP level to be reached. Published data
refer mainly to experimental models using incremental
doses of norepinephrine, with only few clinical studies.

**Experimental data**

Norepinephrine causes vasoconstriction (via alpha-agonist
receptors) with the potential to result in decreased blood
flow to the organs. Accordingly, following norepinephrine
administration, decreased splanchnic [23] and renal [24]
blood flows were observed under various conditions
(hypotension, normotension, and hypertension). Other
studies have reported opposite results. For instance, the
study by Zhang et al. reported that norepinephrine did not
modify hepatic and renal blood flow in dogs submitted to
endotoxin administration [25]. Anderson et al. showed
that, in dogs, incremental norepinephrine doses
(0.1–0.4 µg/kg/min) were associated with increases in
MBP, renal blood flow, and glomerular filtration rate,
along with decreases in renal resistances [26]. Inhibition of
the sympathetic system using pentolinium completely
blocked norepinephrine-induced renal vasodilatation,
enabling the authors to conclude that the vasodilator
actions of norepinephrine were due to increased systemic
BP, which led to decreased sympathetic tonus via the
baroreflex, which in turn induced vasodilatation. Using a
different approach, Di Giantomasso et al. [27] compared
the effects of identical doses of norepinephrine in healthy
and endotoxic dogs. Norepinephrine increased both MBP
and renal blood flow in endotoxic dogs, whereas MBP
elevation in healthy dogs was not associated with
increased renal blood flow. Nevertheless, it must be
stressed that these animal studies do not reflect the
hemodynamic conditions observed in septic shock, which
is generally characterized by a hyperdynamic state com-
bining high CO and low peripheral vascular resistances.

**Clinical data**

As the aim of the present review was to focus on the
target blood pressure and not to discuss the differential
effects of vasoactive drugs both on systemic and regional
blood flows (please see [28, 29]), we selected the few
clinical studies that have addressed the dose–response
effects of vasopressor amines (Table 1). In two studies
[30, 31] in septic shock patients, elevation of MBP from
65 to 85 mmHg with norepinephrine did not result in any
improvement in metabolic parameters and regional per-
fusion at the high MBP level. Deruddre et al. [32],
however, reported increases in cardiac index and diuresis
and a decrease in renal arterial resistance index (measured
using Doppler) when MBP increased from 65 to 75 mmHg with norepinephrine in 11 septic shock
patients. However, when norepinephrine doses were
increased further in order to achieve an MBP of
85 mmHg, no additional benefits were observed. More
recently, two prospective studies assessed macrocircula-
tion and microcirculation with a similar design (increment
of MBP by 10 mmHg). In the study by Jhanji et al. [33],
the increase in MBP from 60 to 90 mmHg increased
cardiac index, cutaneous tissue PT02 (measured using a
Clark electrode), and cutaneous red blood cell flux
(assessed using laser Doppler flowmetry), whereas sub-
lingual microvascular flow (assessed using sidestream
darkfield imaging) did not change. In the study by Dubin
et al. the incremental doses of norepinephrine led to a
progressive increase in MBP (from 65 to 75 mmHg and
then to 85 mmHg) and in oxygen delivery. Overall, these systemic changes did not influence the sublingual microcirculatory blood flow assessed by using sidestream darkfield imaging [34]. However, the sublingual perfusion response was different among individuals. The sublingual perfusion was better for an MBP of 65 mmHg in some patients, for an MBP of 75 or of 85 mmHg in others [34]. Finally, it should be added that in these prospective studies, very few patients were included and the time of equilibrium between the incremental increases in MBP was rather short with a range of 30 min [34] for the shorter time to 4 h for the longer time [30].

Finally, using another approach, Varpula et al. retrospectively assessed the hemodynamic values that were likely to be associated with the patient’s outcome [35]. In their 111-patient cohort, only MBP and venous blood oxygen saturation values were independently associated with mortality. The best predictor of death was the cumulative time spent below the 65 mmHg MBP threshold. Although this threshold must be considered as the minimum MBP target, the value does not represent a fixed and definitive objective during the resuscitation of critically ill patients. The aforementioned studies have several limitations. First, sample sizes were small. Second, the norepinephrine dose increases were tested far after the onset of septic shock. In contrast, clinical studies that revealed the benefits of an aggressive hemodynamic strategy generally included patients straight upon septic shock diagnosis [36]. In their study comparing standard versus aggressive strategy guided by precise hemodynamic objectives (central venous pressure >8 mmHg, MBP > 65 mmHg, diuresis >0.5 mL/kg/h, and ScvO₂ > 70%), Rivers et al. observed statistically significant benefits in terms of mortality and morbidity in the aggressive strategy arm. Interestingly, the MBP of patients of the aggressive strategy arm was significantly higher, at hour 6 of resuscitation, than that measured in patients of the standard strategy arm (95 ± 19 vs. 81 ± 18 mmHg), far beyond the objectives set by the protocol or the current recommendations.

Other prospective studies, which were not aimed at assessing the effects of various MBP levels, reported mean MBP values ranging from 75 to 90 mmHg, without any notable deleterious effects [37–39]. Only one single study evaluating a non-specific NO synthase inhibitor revealed an abnormally high mortality rate in the patient arm receiving this treatment [40]. This abnormally high mortality rate was ascribed to cardiovascular failure and excessive vasoconstriction induced by this agent as suggested by very high MBP (>95 mmHg) levels in 25% of patients receiving the NO synthase inhibitor.

Published data did not reveal whether increasing MBP target above 65 mmHg can actually improve the patient’s survival. Furthermore, target MBP is likely to differ from patient to patient, depending on the underlying condition (preexisting hypertension or cardiovascular disease). Currently, there is no study comparing the effects of two different MBP targets at an early stage of septic shock. The SEPSIS-PAM study (funded by Programme Hospitalier de Recherche Clinique National, 2009, clinicaltrials.gov identifier NCT01149278) has been designed to provide some answers. The study was aimed at comparing two early resuscitation strategies based on two different MBP targets: a control arm (“standard MBP”) with an MBP target between 65 and 70 mmHg, in conformity with the current recommendations, and an interventional arm (“high MBP”) with an MBP target between 80 and 85 mmHg to be reached by using incremental doses of norepinephrine. The main evaluation criterion will be mortality rate, irrespective of the cause, at day 28. The secondary end points of the SEPSIS-PAM trial are related to the potential side effects of increase in MBP during septic shock resuscitation (i.e., life-threatening arrhythmias, acute myocardial infarction, mesenteric ischemia, and digital necrosis). This study, scheduled to include 800 patients, will allow for subgroup analyses, depending on patient’s characteristics such as preexisting hypertension.

### Table 1 Summary of relevant prospective studies

<table>
<thead>
<tr>
<th>Study patients (n)</th>
<th>Incremental increases in the MBP (mmHg) (time for each step of MBP)</th>
<th>Measures</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bourgoin et al. [30] (2 × 14)</td>
<td>MBP 65 versus 85 (4 h)</td>
<td>Hemodynamics, renal function, CI</td>
<td>↑CI</td>
</tr>
<tr>
<td>Ledoux et al. [31] (10)</td>
<td>65, 75, 85 (105')</td>
<td>Hemodynamics, tonometry, laser Doppler, renal function</td>
<td>↑CI</td>
</tr>
<tr>
<td>Deruddre et al. [32] (11)</td>
<td>65, 75, 85 (120')</td>
<td>Hemodynamics, renal function, renal resistance index</td>
<td>For 65–75 mmHg step, ↑urine output, ↓renal resistance index</td>
</tr>
<tr>
<td>Jhanji et al. [33] (16) CCM 2009</td>
<td>60, 70, 80, 90 (45')</td>
<td>Hemodynamics, PtO₂, LD, SDI</td>
<td>↑DO₂, ↑PtO₂↑LD, SDI ns</td>
</tr>
<tr>
<td>Dubin et al. [34] (20)</td>
<td>65, 75, 85 (30')</td>
<td>Hemodynamics, tonometry, SDI</td>
<td>↓CI, DO₂ ns, tonometry ns, SDI ns</td>
</tr>
</tbody>
</table>

MBP mean blood pressure, CI cardiac index, PtO₂ cutaneous tissue PtO₂, LD laser Doppler. SDI sidestream darkfield imaging, DO₂ oxygen delivery, ns result not significant.
Conclusion

Invasive BP monitoring seems indispensable for guiding resuscitation of patients with circulatory shock, as it provides reliable and continuous MBP values. The optimal MBP target remains a matter of debate and justifies being pursued in both clinical and fundamental research.

In addition to MBP levels, the BP curve provides valuable information. Its correct interpretation may help to identify the mechanisms responsible for the hemodynamic failure, thereby guiding fluid therapy and vasoactive drugs administration.

References