A rational approach to fluid therapy in sepsis

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Abstract

Aggressive fluid resuscitation to achieve a central venous pressure (CVP) greater than 8 mm Hg has been promoted as the standard of care, in the management of patients with severe sepsis and septic shock. However recent clinical trials have demonstrated that this approach does not improve the outcome of patients with severe sepsis and septic shock. Pathophysiologically, sepsis is characterized by vasoplegia with loss of arterial tone, venodilation with sequestration of blood in the unstressed blood compartment and changes in ventricular function with reduced compliance and reduced preload responsiveness. These data suggest that sepsis is primarily not a volume-depleted state and recent evidence demonstrates that most septic patients are poorly responsive to fluids. Furthermore, almost all of the administered fluid is sequestered in the tissues, resulting in severe oedema in vital organs and, thereby, increasing the risk of organ dysfunction. These data suggest that a physiologic, haemodynamically guided conservative approach to fluid therapy in patients with sepsis would be prudent and would likely reduce the morbidity and improve the outcome of this disease.

Key words: central venous pressure; fluid therapy; pulmonary edema; sepsis; septic shock

Editor’s key points

• The authors review, in detail, the physiology of hypo- and hypervolaemia, and the effects of venodilation and arteriodilation.
• They contend that universal, aggressive fluid administration in septic shock carries considerable risk, and that a haemodynamically-guided, conservative approach is likely to produce better outcome.
• They also argue that early norepinephrine therapy is likely to improve outcome.

In the 19th century, patients with cholera dying from hypovolaemic shock were treated by venesection or blood-letting. This treatment was considered the standard of care for this disorder. In the first part of the 21st century patients with septic shock were treated with massive amounts of crystalloids, approaching 17 litres in the first 72 h of hospitalization. This approach was considered the standard of care and endorsed by International Guidelines. Clearly, these treatment approaches failed to appreciate the pathophysiological changes of both disorders and that the prescribed treatments were harmful. Cholera is a disease associated with profound volume depletion through diarrhoea that requires replacement with i.v. fluids. Severe sepsis and septic shock however, are not associated with volume loss. Sepsis is characterized by arterio- and venodilation together with microcirculatory and myocardial dysfunction, with septic patients being poorly responsive to fluid administration. Nevertheless, aggressive fluid resuscitation to achieve a central venous pressure (CVP) greater than 8 mm Hg (‘Early Goal Directed Therapy’ - EGDT), has been considered the standard of care in the management of patients with severe sepsis and septic shock. However, recent multicentre clinical trials (ProCESS, ARISE and PROMISE) and a meta-analysis of EGDT have demonstrated that this approach does not improve the outcome of patients with severe sepsis and septic shock. This article reviews the haemodynamic changes associated with sepsis and provides a rational approach to fluid management in this complex disorder.
Pertinent normal cardiovascular physiology

The amount of blood pumped out of the heart (cardiac output) is equivalent to venous return (volume entering the right atrium).12 According to Guyton, venous return is determined by the pressure gradient between the peripheral veins and the right atrium (CVP).13 The venous system can be divided into two theoretical compartments, the unstressed and stressed volume.14 The intravascular volume that fills the venous system to the point where intravascular pressure starts to increase is called unstressed volume, whereas the volume that stretches the veins causes intravascular pressure to increase is called the stressed volume. The mean circulatory filling pressure (MCFP) is conceptualized as the pressure distending the vasculature, when the heart is stopped (zero flow) and the pressures in all segments of the circulatory system have equalized.15 16 The stressed venous system is the major contributor to the MCFP.14 15 The MCFP in humans is normally in the range of 8–10 mm Hg.14 15 The MCFP is the major determinant of venous return.

The venous system has a large vascular capacitance and a constant compliance in which an increased blood volume is associated with a relatively small change in the MCFP.14 However, because of the restraining effects of the pericardium and cardiac cytoskeleton, the diastolic compliance of the normal heart (both left and right ventricles) reduces as distending volume increases; consequently, with large volume fluid resuscitation, the cardiac filling pressures (particularly on the right side, i.e. CVP) increase faster than the MCFP, decreasing the gradient for venous return.16–18 Organ blood flow is determined by the difference in the pressure between the arterial and venous sides of the circulation. The mean arterial pressure (MAP) minus the CVP is therefore the overall driving force for organ blood flow. A high CVP therefore decreases the gradient for venous return, while at the same time decreasing organ driving pressure and therefore blood flow. Venous pressure has a much greater effect on microcirculatory flow than the MAP; provided that the MAP is within an organ’s autoregulatory range, the CVP becomes the major determinant of capillary blood flow.19 20

According to the Frank-Starling principle, as left-ventricular (LV) end-diastolic volume (i.e. preload) increases, LV stroke volume (SV) increases until the optimal preload is achieved, at which point the SV remains relatively constant.21 This optimal preload is related to the maximal overlap of the actin-myosin myofibrils. Fluid administration will only increase SV if two conditions are met, namely: i) that the fluid bolus increases the MCFP more than it increases the CVP, thereby increasing the gradient for venous return, and ii) that both ventricles are functioning on the ‘ascending limb’ of the Frank-Starling curve.22 23

The vascular endothelium is coated on the luminal side by a web of membrane-bound glycoproteins and proteoglycans known as the endothelial glyocalyx.24–26 The glyocalyx plays a major role as a vascular barrier, preventing large macromolecules moving across the endothelium, preventing leucocyte and platelet aggregation and limiting tissue oedema. An intact endothelial glyocalyx is a prerequisite of a functioning vascular barrier.27 Increased cardiac filling pressures after aggressive fluid resuscitation increase the release of natriuretic peptides.28 29 Natriuretic peptides cleave membrane-bound proteoglycans and glycoproteins (most notably syndecan-1 and hyaluronic acid) off the endothelial glyocalyx.30–32 Damage to the glyocalyx profoundly increases endothelial permeability. In addition, increased natriuretic peptides inhibit the lymphatic propulsive motor activity reducing lymphatic drainage.33–35

Vascular dysfunction with sepsis

Septic shock is primarily a vasoplegic state with arterial and venous dilatation, as a result of failure of the vascular smooth muscle to constrict.36 Vasoplegic shock is believed to be because of increased expression of inducible nitric oxide synthetase with increased production of nitric oxide (NO), activation of KATP channels resulting in hyperpolarisation of the muscle cell membrane, increased production of natriuretic peptides (which act synergistically with NO) and a relative vasopressin deficiency.37 Arterial dilatation results in systemic hypotension. However, more importantly, profound venodilation occurs in the splanchnic and cutaneous vascular beds increasing the unstressed blood volume, decreasing venous return and cardiac output.14 15 As approximately 70% of the blood volume is within the venous system, changes in venous blood volume play a major role in determining venous return.15

Sepsis is characterized by increased expression and activation of endothelial adhesion molecules with adhesion and activation of platelets, leucocytes and mononuclear cells and activation of the coagulation cascade.37 This results in a diffuse endothelial injury, microvascular thrombosis, gaps between the endothelial cells (paracellular leak) and shedding of the endothelial-glyocalyx.38 39 The combination of these mechanisms contributes to a reduction in functional capillary density, heterogeneous abnormalities in microcirculatory blood flow and increased capillary permeability.40 41

Cardiac changes with sepsis

Myocardial depression in patients with septic shock was first described in 1984 by Parker and colleagues42 using radionuclide cineangiography. In a series of 20 patients, these investigators reported a 50% incidence of LV systolic dysfunction. Notably, in this study the initial ejection fraction and ventricular volumes were normal in non-survivors and these indices did not change during serial studies; it is likely that these patients had significant diastolic dysfunction. The initial studies evaluating cardiac function in sepsis focused on LV systolic function. However, LV diastolic dysfunction has emerged as a common finding in patients with severe sepsis and septic shock.43 Adequate filling during diastole is a crucial component of effective ventricular pump function. Diastolic dysfunction refers to the presence of an abnormal LV diastolic distensibility, filling, or relaxation, regardless of LV ejection fraction. Predominant diastolic dysfunction appears to be at least twice as common as systolic dysfunction in patients with sepsis.44 In the largest study to date (n=262), Landesberg and colleagues44 reported diastolic dysfunction in 54% of patients with sepsis while 23% of patients had systolic dysfunction. Brown and colleagues45 performed serial echocardiograms in 78 patients with severe sepsis or septic shock. In this study 62% of patients had diastolic dysfunction on at least one echocardiogram. Unlike systolic LV dysfunction, diastolic dysfunction is an important prognostic marker in patients with sepsis.46–48 Diastolic dysfunction is becoming increasingly recognized in the community, particularly in patients with hypertension, diabetes, obesity and with advancing age.49–51 These conditions are associated with an increased risk of sepsis and may therefore further increase the prevalence and severity of diastolic dysfunction in patients with sepsis. Patients’ with diastolic dysfunction respond very poorly to fluid loading.64 This was demonstrated in a landmark study published by Ognibene and colleagues65 in 1988, who reported an insignificant increase LV stroke work index and LV end-diastolic volume index in patients with septic
shock who received a fluid challenge. In these patients, fluid loading will increase cardiac filling pressures, increase venous and pulmonary hydrostatic pressures with the increased release of natriuretic peptides with minimal (if any) increase in SV. Furthermore, as reviewed above, aggressive fluid resuscitation in itself causes diastolic dysfunction which will compound the pre-existing and/or sepsis-induced diastolic dysfunction.

**Fluid responsiveness**

The widely accepted rationale behind fluid resuscitation in sepsis is to improve cardiac output and organ perfusion, thereby limiting organ dysfunction. Logically, therefore, the only reason to resuscitate a patient with fluid (give a fluid bolus) would be to cause a clinically significant increase in SV. A patient whose SV increases by 10–15% after a fluid challenge (250–500 ml) is considered to be a fluid responder. Nonetheless, according to the Frank-Starling principle, as the preload increases, SV increases until the optimal preload is achieved, at which point the SV remains relatively constant. If the fluid challenge does not increase SV, volume loading serves the patient no useful benefit and is likely harmful. The adverse effects of fluid loading when a patient is on the flat portion of the Frank-Starling curve, is related to the curvilinear shape of the left ventricular pressure-volume curve, resulting from altered diastolic compliance at higher filling pressures. As the patient reaches the plateau of his/her Frank-Starling curve, atrial pressures increase, increasing venous and pulmonary hydrostatic pressures which combined with the increased release of natriuretic peptides, causes a shift of fluid into the interstitial space, with an increase in pulmonary and tissue oedema (see Fig. 1). Tissue oedema impairs oxygen and metabolite diffusion, distorts tissue architecture, impedes capillary blood flow and lymphatic drainage and disturbs cell-cell interactions. Increased right atrial pressure (CVP) is transmitted backwards increasing venous pressure in vital organs, with a profound effect on microcirculatory flow and organ function. The kidney is particularly affected by increased venous pressure, which leads to increased renal subcapsular pressure and reduced renal blood flow and glomerular filtration rate.

**Fluid responsiveness and the haemodynamic effects of fluids in patients with sepsis**

Studies in heterogeneous groups of critically ill and injured patients and those undergoing surgery have reproducibly demonstrated that only about 50% of haemodynamically unstable patients are fluid responders. This is a fundamental concept which is not widely appreciated, and challenges the widely accepted notion that fluid administration is the ‘cornerstone of resuscitation’. As a result of the effects of sepsis on the venous capacitance vessels and myocardial function, it is likely that less than 40% of hypotensive patients with severe sepsis or septic shock are ‘fluid responders’.

The goal of fluid resuscitation is to increase the stressed blood volume and MCFP more than the CVP, and thereby increase the pressure gradient for venous return. However the ability of crystalloids (the most common fluid used for the resuscitation of patients with sepsis) to expand the intravascular volume is poor. Chowdhury and colleagues reported that in healthy volunteers, only 15% of a crystalloid bolus remained in the intravascular space at 3 h, with 50% of the infused volume being in the

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**Fig 1** Superimposition of the Frank-Starling and Marik-Phillips curves demonstrating the effects of increasing preload on stroke volume and lung water in a patient who is preload responsive (A) and non-responsive (B). With sepsis the EVLW curve is shifted to the left. EVLW=extra-vascular lung water; CO=cardiac output; SV=stroke volume. MCFP=mean circulating filling pressure. Reproduced with permission from the British Journal Anaesthesia; 2014;12:620–622.
extravascular extracellular compartment. In patients with sepsis and in experimental models, less than 5% of a crystalloid bolus remains intravascular an hour after the end of the infusion.¹⁴ ⁵⁵ It is therefore likely that the haemodynamic effects of a fluid bolus (in the fluid responders) are short-lived, with the net effect being the shift of fluid into the interstitial compartment with tissue oedema. Nunes and colleagues⁶⁵ demonstrated that in fluid responders, the SV returned to baseline 60 min after a crystalloid bolus. Glassford and colleagues⁶⁷ performed a systematic review which examined the haemodynamic response of fluid boluses in patients with sepsis. These authors reported that while the mean arterial pressure (MAP) increased by 7.8 (3.8) mm Hg immediately after the fluid bolus, the MAP had returned close to baseline at one hour with no increase in urine output. In a retrospective analysis of the ARDSnet Fluid and Catheter Treatment Trial (FACTT),⁶⁸ Lammi and colleagues⁶⁶ examined the physiological effect of 569 fluid boluses (15 ml kg⁻¹; 1025±243 ml) in 127 patients (the majority of whom were septic), randomized to the pulmonary artery catheter arm of the study. The FACTT trial required reassessment of the haemodynamic profile one hour after the fluid bolus, if the indication for fluids was shock, ineffective circulation, or low urine output and four hours if the indication was a low pulmonary artery occlusion pressure (PAOP).⁵⁶ Fifty-eight percent of fluid boluses were given for shock or poor urine output/ineffective circulation, with 42% of boluses given for a low PAOP. In this study, only 23% of patients were fluid responders (increase in CI > 15%). There was a small increase in the MAP (78.3±16.4 to 80.4±16.5 mm Hg) while the urine output did not change in the 1–4 h after the fluid bolus.

Monge-Garcia and colleagues⁶⁹ measured the effects of a fluid bolus on arterial load in patients with septic shock. In this study 67% of patients were fluid responders, however the MAP increased in only 44% of these patients (pressure responder). Overall there was a significant reduction in effective arterial elastance (Ea) and systemic vascular resistance (SVR), this effect being most marked in the pre-load responders who were pressure non-responders. Additional studies have demonstrated a decrease in SVR after fluid resuscitation in patients with sepsis.⁷⁰ ⁷¹ This suggests that fluid boluses should be considered vasodilator therapy, in patients with sepsis and that aggressive fluid resuscitation may potentiate the hyperdynamic state.

In summary, these studies demonstrate that the majority of patients with severe sepsis and septic shock are not fluid responders. Furthermore, the haemodynamic changes in the fluid responders are small, short-lived and likely to be clinically insignificant. However, aggressive fluid resuscitation will likely have adverse haemodynamic consequences including an increase in cardiac filling pressures, damage to the endothelial glycoalyx, arterial vasodilation and tissue oedema. Consequently, the concept that aggressive fluid resuscitation is the ‘cornerstone of resuscitation’ of patients with severe sepsis and septic shock needs to be reconsidered.⁵ ⁶ ⁷ ⁵⁹ Indeed, it is likely that aggressive fluid resuscitation increases the morbidity and mortality of patients with sepsis (see section below). Nevertheless the updated Surviving Sepsis Campaign Guidelines, published after the publication of the ProCESS, ARISE and PROMISE studies—¹⁰ mandate the administration of ‘30 ml kg⁻¹ crystalloid for hypotension or lactate ≥4 mmol L⁻¹ within 3 h of presentation to hospital.’⁷² This recommendation is problematic as the majority of hypotensive patients with septic shock will not respond to fluids; this approach is likely to lead to ‘salt water drowning’ with an increase in the morbidity and mortality of these patients.⁷² Furthermore, as discussed below, an increased blood lactate is unlikely to be associated with anaerobic metabolism, or inadequate oxygen delivery, and attempts at increasing oxygen delivery do not increase oxygen consumption or lower lactate concentrations. Indeed such an approach has been demonstrated to increase the risk of death of critically ill patients.⁷⁴

These data suggest that only patients who are fluid responsive should be treated with fluid boluses. Furthermore, the patients’ fluid responsiveness and the risk/benefit ratio of fluid administration needs to be determined before each fluid bolus.⁷⁵ As the haemodynamic response to a fluid challenge is very short-lived and large fluid boluses (20–30 ml kg⁻¹) are associated with severe volume overload, the mini-fluid bolus approach (200–500 ml) to fluid therapy is recommended.⁷⁶ The passive leg raising manoeuvre (PLR) and the fluid bolus test coupled with real-time SV monitoring, are currently the only techniques which have an acceptable degree of clinical accuracy, which can be used for determining fluid responsiveness.⁷⁷ Because of its ease of use, simplicity, high diagnostic accuracy, inherent safety and short procedure time (less than 5 min to perform) the PLR is the preferred method to assess fluid responsiveness in the emergency department, hospital ward and ICU.⁷⁸ ⁷⁹ ⁸⁰ The PLR manoeuvre is performed by lifting the legs passively from the horizontal position and is associated with the gravitational transfer of blood (about 300 ml) from the lower limbs and abdomen toward the intrathoracic compartment.⁷³ ⁷⁷ ⁷⁸ The PLR manoeuvre has the advantage of reversing its effects once the legs are returned to the horizontal position.⁷⁵ ⁷⁹ ⁸⁰ Therefore, the PLR manoeuvre is considered a reversible or ‘virtual’ fluid challenge. The ability of the PLR manoeuvre to serve as a test of preload responsiveness has been confirmed in multiple studies performed in critically ill patients. A meta-analysis, which pooled the results of eight studies, confirmed the excellent value of PLR to predict fluid responsiveness in critically ill patients with a global area under the ROC curve of 0.95 (95% CI, 0.92–0.99). In an updated meta-analysis which evaluated 21 studies, we report a pooled ROC AUC of 0.93–0.95 (Monnet X, Marik P, Teboul JL; submitted for publication). As the maximal haemodynamic effects of PLR occur within the first min of leg elevation,⁷⁷ ⁸¹ it is important to assess these effects with a method able to track changes in cardiac output or SV on a real-time basis. It is important to note that the change in bp after a PLR or fluid challenge is a poor guide to fluid responsiveness; SV may increase without a significant change in bp.⁷⁰ Furthermore, unlike techniques to determine fluid responsiveness based on heart-lung interactions, the PLR manoeuvre can be performed in spontaneously breathing patients, patients with cardiac arrhythmias and those receiving low tidal volume ventilation.⁷⁵ ⁵¹

The chest radiograph, CVP, central venous oxygen saturation (ScvO₂) and ultrasonography, including the vena-caval collapsibility index, have limited value in guiding fluid management and should not be used for this purpose.⁵⁴ ⁸² ⁸⁶ Furthermore, it has been well established that physical examination cannot be used to predict fluid responsiveness and physical examination is unreliable for estimating intravascular volume status.⁸⁷ It is therefore very troubling that the updated Surviving Sepsis Campaign Guidelines which are now federally mandated in the USA (SEP-1 Early Management Bundle, #0500 Severe Sepsis and Septic Shock: management Bundle) require either a ‘focused exam by a licensed independent practitioner’, or measurement of the CVP or ScvO₂, or bedside cardiovascular ultrasound, to assess the volume status of the patient with severe sepsis and septic shock.⁸⁸ It should be noted that the area under the receiver operator characteristic (ROC) curve of the CVP, for predicting fluid responsive is approximately 0.5, which is considered a ‘completely useless test’.⁵⁴ ⁸⁹ ⁹⁰ Furthermore, it is important to emphasize
that a normal CVP is between 0–2 mm Hg; this is necessary to ensure adequate venous return and cardiac output (as discussed above). In addition, while the change in CVP in response to a fluid challenge is still widely promoted as a method to guide fluid therapy, this technique has no physiologic basis and is unable to predict fluid responsiveness with any degree of accuracy. Furthermore, it should be noted that with the exception of measuring dynamic changes in the carotid Doppler peak velocity, bedside ultrasound including the inferior vena cava distensibility index cannot accurately predict fluid responsiveness. It is somewhat astonishing that the ScvO2 is still being recommended to guide the resuscitation of critically ill septic patients and is being used as an indicator of the quality of care delivered. Monitoring the ScvO2 in patients with sepsis has no scientific basis, as patients with sepsis usually have a normal or increased ScvO2 and a high (ScvO2 > 90%) rather than low ScvO2 has been demonstrated to be an independent predictor of death. Three large randomized controlled trials (ProCESS, ARISE and PROMISE) have now demonstrated that titrating therapy to a ScvO2 > 70% does not improve outcome, but rather increases the risk of organ dysfunction, length of ICU stay and increased use of resources and costs. These observations must lead to the conclusion that the original EGDT study was not scientifically valid and that no aspect of this study should be used to guide the management of patients with severe sepsis and septic shock.

In addition to targeting a CVP greater than 8 mm Hg, the Surviving Sepsis Campaign guideline recommends ‘targeting resuscitation to normalize lactate in patients with elevated lactate levels as a marker of tissue hypoperfusion.’ This recommendation is based on the notion that an elevated lactate is a consequence of tissue hypoxia and inadequate oxygen delivery. However, these assertions are likely wrong. Hotchkiss and Karl in a seminal review published over 20 yr ago, demonstrated that cellular hypoxia and bioenergetic failure does not occur in sepsis. It has now been well established that epinephrine released as part of the stress response in patients with severe sepsis, stimulates Na+ K+-ATPase activity. Increased activity of Na+ K+ ATPase leads to increased lactate production under well-oxygenated conditions in various cells, including erythrocytes, vascular smooth muscle, neurons, glia, and skeletal muscle. While sepsis is considered to be a ‘hypermetabolic’ condition oxygen consumption and energy expenditure are broadly comparable with that of normal people, with energy expenditure decreasing with increasing sepsis severity. Therefore, there is no requirement that oxygen delivery increase with sepsis. Indeed, increasing oxygen delivery in patients with sepsis does not increase oxygen consumption nor decrease lactate concentrations. The critical oxygen delivery threshold for humans (both septic and non-septic) is approximately 3.8 (1.5) ml min⁻¹ kg⁻¹ (270 ml min⁻¹ in a 70 kg patient). These values translate into a cardiac output of approximately 2 litre min⁻¹; it is likely that only pre-terminal moribund patients with septic shock would have such a low cardiac output.

**Evidence supporting the deleterious effects of aggressive fluid resuscitation**

The harmful effects of aggressive fluid resuscitation on the outcome of sepsis are supported by experimental studies and data accumulated from clinical trials. Multiple clinical studies have demonstrated an independent association between an increasingly positive fluid balance and increased mortality in patient with sepsis. The most compelling data that fluid loading in sepsis is harmful, comes from the landmark ‘Fluid Expansion as Supportive Therapy (FEAST)’ study performed in 3141 sub-Saharan children with severe sepsis. In this randomized study, aggressive fluid loading was associated with a significantly increased risk of death. After the Rivers’ Early Goal Directed Therapy trial, which formed the basis for the concept of early aggressive fluid resuscitation, a number of EGDT studies have been published. An analysis of these studies demonstrates a marked reduction in mortality over this time period (see Fig. 2). While all these studies emphasized the early use of appropriate antibiotics, the decline in the amount of fluids administered in the first 72 h is striking. Furthermore as illustrated in Fig. 3 there is a very strong correlation between the amount of fluid administered (in first 6 h) and the target CVP. It should be noted that the CVP in the usual arm of both the ARISE (The Australasian Resuscitation in Sepsis Evaluation) and ProMISe (Protocolised Management in Sepsis) trials was greater than 10 mm Hg, being almost identical to the EGDT arm, and with
almost an identical amount of fluid being administered in the usual arm, as in the active EGDT arm in both studies.\textsuperscript{9, 10} Clinicians seem compelled to give fluid when the CVP is less than 8 mm Hg; the only solution to this pervasive problem is to stop measuring the CVP.

A haemodynamically-guided conservative fluid resuscitation strategy

These data strongly support a haemodynamically-guided fluid resuscitation strategy in patients with severe sepsis and septic shock. Furthermore, from an evolutionary point of view, humans have evolved to deal with hypovolemia and not hypervolemia. Large fluid boluses may counter the life preserving homeostatic mechanisms in unstable critically ill patients, increasing the risk of death.\textsuperscript{123} In some patients, hypotension and tachycardia do resolve with limited fluid resuscitation. It is likely that many of these patients have super-added dehydration as a result of poor oral intake and a delay in seeking medical attention. However, fluids alone will not reverse the haemodynamic instability of patients with more severe sepsis; in these patients, fluids alone are likely to exacerbate the vasodilatory shock and increase the capillary leak and tissue oedema. Based on these data, the initial resuscitation of patients with septic shock should logically include at most 500 ml boluses of crystalloid (Ringer’s lactate), to a maximum of about 20 ml kg\textsuperscript{-1}.\textsuperscript{1, 124} Ideally, fluid resuscitation should be guided by the determination of fluid responsiveness.\textsuperscript{10, 51} Normal saline is an ‘unphysiologic’ solution that should be avoided, except in patients with acute neurological injuries. Normal saline causes a hyperchloremic metabolic acidosis\textsuperscript{125–128}; it decreases renal blood flow\textsuperscript{63} increasing the risk of renal failure.\textsuperscript{129} In patients with sepsis, the use of normal saline as compared with physiologic salt solutions, has been associated with an increased risk of death.\textsuperscript{130} Similarly, synthetic starch solutions increase the risk of renal failure and death in patients with sepsis and should be avoided.\textsuperscript{131–132}

The septic patient with an intra-abdominal catastrophe, who requires urgent surgical intervention, represents a sub-group of patients that may require more aggressive fluid resuscitation. However, overly aggressive fluid resuscitation will likely result in intra-abdominal hypertension, which is associated with a high risk of complications and death.\textsuperscript{133, 134} In these patients continuous SV monitoring is essential and ongoing fluid requirements should be guided by the trend in the SV and the haemodynamic response to a mini-fluid bolus. In addition, perioperative, intra-abdominal pressure monitoring is required in these patients.\textsuperscript{133}

Norepinephrine should be initiated in those patients who remain hypotensive (MAP < 65 mm Hg) despite this initial, limited fluid strategy.\textsuperscript{124, 135} Norepinephrine increases arterial vascular tone increasing bp and organ blood flow. Venous capacitance vessels are much more sensitive to sympathetic stimulation than are arterial resistance vessels, consequently low dose α-1 agonists cause greater veno- than arterio-constriction.\textsuperscript{136} In septic patients, α-1 agonists mobilize blood from the unstressed reservoirs in the splanchnic circulation and skin, thereby increasing venous return and cardiac output. In a porcine endotoxic shock model, Datta and Magder\textsuperscript{137} demonstrated that norepinephrine increased the MCFP, leading to an increase in venous return. Similarly in patients with septic shock, Persichini and colleagues\textsuperscript{138} demonstrated that decreasing the dose of norepinephrine, decreased the MCFP with a decrease in venous return and cardiac output. In a cohort of patients with septic shock Kozieras and colleagues\textsuperscript{139} demonstrated that norepinephrine increased cardiac index, systemic vascular resistance and central blood volumes (intrathoracic blood volume, global end-diastolic volume), as measured by transpulmonary thermodilution. In this study extra-vascular lung water (EVLW) remained unchanged. Hamzaoui and colleagues\textsuperscript{140} demonstrated that the early administration of norepinephrine increased preload, cardiac output and MAP largely reversing the haemodynamic abnormalities of severe vasodilatory shock. Abid and colleagues\textsuperscript{141} demonstrated that the early use of norepinephrine in patients with septic shock was a strong predictor of survival. These studies demonstrate that in patients with septic shock, the early use of norepinephrine restores the stressed blood volume, increasing the MCFP, venous return and cardiac output. The increase in the stressed blood volume is as a result of the mobilisation of blood, rather than the short-lived effect of a volume expander. Therefore unlike fluids, the effect of α-1 agonists on venous return is enduring and not associated with tissue oedema. α-1 agonists should not be used in patients with hypovolaemic shock (e.g. cholera) who are already venoconstricted; in this setting, α-1 agonists will cause severe vasoconstriction, impairing organ blood flow. However, in septic veno- and arterio-dilated patients, α-1 agonists increase venous return, increase stroke volume and increase arterial tone, thereby increasing organ blood flow.\textsuperscript{142–144} Digital and limb ischaemia and ischaemic skin lesions are extremely rare with the use of norepinephrine,\textsuperscript{145} occurring usually with high dosages and usually when used together with vasopressin.\textsuperscript{146, 147} Furthermore, uncontrolled disseminated intravascular coagulation (DIC) plays a contributing role in these patients.\textsuperscript{148} We are unaware of any reported patients with digital or limb ischaemia associated with the early use of norepinephrine. In our experience the early use of norepinephrine appears to reduce the peak and total dose of vasopressors administered. It is noteworthy that norepinephrine may be safely given through a well-functioning peripheral venous catheter,\textsuperscript{149} precluding the requirement for emergent central venous catheterization, which is generally regarded as an obstacle to the early use of norepinephrine. In experimental sepsis models, norepinephrine appears preferable to epinephrine and phenylephrine as a first-line therapy in restoring haemodynamic stability.\textsuperscript{150, 151} Dopamine as opposed to norepinephrine is associated with an increased risk of arrhythmias and death in patients with sepsis and should be avoided.\textsuperscript{152–154}

Conclusions

An emerging body of basic science and clinical studies supports the concept of a haemodynamically-guided, restricted fluid resuscitation strategy in patients with severe sepsis and septic shock. Initial fluid resuscitation should be limited and guided by an assessment of fluid responsiveness. Norepinephrine increases preload, systemic vascular resistance and cardiac output and its use in patients with persistent hypotension is recommended early in the course of septic shock. Early bedside echocardiographic assessment of cardiac function is recommended to guide further haemodynamic management. Adequately powered, randomized, controlled trials, are urgently required to demonstrate the benefits of the early use of norepinephrine and a conservative, haemodynamically-guided fluid resuscitation strategy.

Authors’ contributions

Writing paper: P.M., R.B.
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