HEMODYNAMIC MONITORING IN BURN RESUSCITATION: CURRENT STATUS

MONITORAGE DU REMPLISSAGE VASCULAIRE INITIAL DES BRÛLÉS : ÉTAT DES LIEUX

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SUMMARY. The science and treatment of burn shock has continued to evolve in tandem with emerging technologies. Burn resuscitation attempts to deliver the appropriate amount of fluid to counteract the detrimental effects of shock, but advances in data collection, processing and analysis have failed to significantly move the needle. This is because there is little consensus about which markers accurately and dynamically predict the body's intravascular volume, a knowledge gap which only widens as each new technology generates more usable data. Here we review the lessons learned.

Keywords: hemodynamic monitoring, goal-directed, burn resuscitation, endpoint, shock

RÉSUMÉ. *Les connaissances et le traitement concernant le choc initial des brûlés évoluent concomitamment à la mise à disposition de nouvelles technologies. Le but du remplissage initial est d'apporter un volume de liquide suffisant pour contrer les effets du choc mais, malgré l'étude de grandes séries, nous ne disposons pas de méthode de surveillance stable. Ceci car il n'existe pas de consensus quant aux marqueurs statiques ou dynamiques reflétant le volume intravasculaire. Et les différences de vues sont plus importantes à chaque fois qu'une nouvelle technologie amène des données nouvelles. Cette article revoit les leçons tirées au fur et à mesure.*

Mots-clés : *monitorage hémodynamique, remplissage vasculaire, cible, adaptation, choc*

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Introduction

The degree of shock from a massive thermal burn is both devastating and dynamic, making its treatment one of the most challenging components of acute burn care. Precise restoration of intravascular volume is crucial to counteracting the fluid shifts and cardiac dysfunction that define burn shock. In 1968, Charles Baxter published calculations to predict initial 24-hour fluid requirements based on body size and burn severity.[1] Dr. Basil Pruitt published his own data out of San Antonio predicting both crystalloid and colloid fluid requirements.[2] These calculations helped to formalize the concept of burn resuscitation and reduce mortality related to burn shock and acute renal failure.[3] Indiscriminate use of fluid leading to over-resuscitation can also be lethal, leading to compartment syndromes and pulmonary complications. Urine output (UOP) continues to be the most commonly used endpoint of resuscitation, despite a lack of high-quality data validating its use as a marker of end-organ perfusion.[4] Other endpoints (mean arterial pressure, base deficit, lactate, hemoglobin) are also frequently used in practice, but the degree to which they should guide resuscitation is still highly controversial.

Hemodynamic monitoring allows for pressure or volume-based assessment of cardiovascular performance. This has led to improvements in the management of sepsis,[5] heart failure,[6] and in cardiac surgery.[7] Attempting to replicate these results in acutely burned patients has mostly been a disappointment, but with each new technology there is renewed interest in its application to burn shock. This interest stems, in part, from a need to shift burn care away from a "one size fits all" approach to a more individualized strategy. The World Health Organization predicts an increase in the population of 60 and older from 12% to 22% by 2050.[8] The higher rate of co-morbidities in this population undoubtedly impacts their burn resuscitation. Arterial waveform analysis and miniaturized trans-esophageal echocardiography are relatively new technologies that should be further investigated within the larger context of lessons learned.

Burn shock

Profound hemodynamic changes occur following severe thermal injury. The inflammatory response immediately post-burn causes capillary disruption and a strongly negative interstitial pressure resulting in fluid egress and accumulation in both burned and unburned tissue. This loss of circulating plasma volume leads to a sequence of events beginning with pre-load reduction and ending with dramatically impaired cardiac performance. This myocardial dysfunction is the result of a complex interplay between volume depletion, oxygen supply and demand, afterload increase, and circulating acute phase reactants.[9-11] Injury to the myocardium has been demonstrated in animal models after thermal burns. Maass et al. compared in vivo assessment of cardiac performance by transthoracic echocardiography with in vitro examination of myocardium in awake mice. The authors found a 26% reduction in fractional shortening by 12 hours post-burn that slowly recovered over the next 3 days.[11] Catecholamines support the body through this depressive state, eventually tipping the patient's physiology to a hyperdynamic state, characterized by profound tachycardia, increased contractility, increased cardiac output, and increased myocardial oxygen consumption.[12]

Burn resuscitation aims to counter the massive fluid shifts and to support cardiac output. This is accomplished by administering a large volume of crystalloid fluid, especially within those first 24 hours. Despite multiple formulas that attempt to predict fluid requirements based on body weight and burn size, the optimal amount of fluid is still an elusive principle with a narrow therapeutic margin between under and over-resuscitation. Replenishing intravascular volume (volume loading) restores preload, thus improving cardiac performance and the overall delivery of oxygen.[13] Urine output is the most commonly employed endpoint to adjust the amount of fluid administered. It can often be unreliable since it is dependent on factors such as circulating glucose, alcohol consumption, drug exposure, and chronic kidney disease.[14] There is also a lag effect that has been observed in response to changes in fluid delivery.[15] Serum lactate, a byproduct of anaerobic conditions and base deficit is also widely used in clinical

practice, but without high-quality data to support.[3] Vital signs alone are a poor indicator of intravascular fluid status.[16] Hemodynamic endpoints present an attractive alternative to urine output with the thought that earlier upstream detection of shock could potentially result in improved tissue preservation.

Pulmonary artery catheter

Pulmonary artery catheters (PAC) were routinely used in massive thermal injuries and generated real-time cardiac and pulmonary pressures. The first major rebuttal to burn resuscitation came in the 1980s when it was proposed in trauma literature that maximizing oxygen delivery could improve survival. Early adopters advocated for using supraphysiologic endpoints for resuscitation. Barton et al. published a protocol in 1997 that augmented an infusion rate predicted by the Parkland formula with colloid and blood products to achieve a pulmonary artery wedge pressure (PAWP) of 15 mmH_20. Despite administering 63% more fluid than predicted by Parkland in the first 24 hours, the authors were unable to restore a "normal preload" in the majority of patients. The mean PAWP increased from 9 to 12 mmH_20, with a corresponding increase in cardiac index (CI) from 2.5 to 4.5 L/min/m^2. The authors noted that their patients had 3-4 times more urine output than would normally be considered adequate.[17] Within several years, there were other studies all in support of a so-called hyperdynamic resuscitation. Most of the studies were statistical comparisons between survivors and non-survivors. The observation that survivors demonstrated a quicker normalization of hemodynamic parameters led the authors to advocate for goal-directed restoration of preload to achieve a hyperdynamic state that would theoretically maximize oxygen delivery. In all cases, the treatment groups received substantially more fluid than predicted by Parkland. There is a paucity of information in these studies regarding complications related to the resuscitation.[18-21]

The routine use of PACs began to decline after a randomized controlled trial found no benefit to PAC-guided therapy over standard of care in high-risk surgical patients.[22] Their use in burn resuscitation was cautioned given the lack of correlation between PAWP, cardiac output, and measured blood volume.[23] Additionally, the accuracy of both central venous pressure (CVP) and PAWP to estimate left ventricular diastolic volume (preload) was called into question by Kumar et al.[24] Since standard barometric parameters are highly dependent on ventricular compliance, the volume/pressure relationship becomes unpredictable in critical illness.

Transpulmonary thermodilution

Transpulmonary thermodilution (TPTD) offered a promising, less invasive alternative to hemodynamic monitoring. This is the process by which a bolus of cold saline is injected through a central vein and the temperature differential is processed by a thermistor at the end of an arterial catheter. Analysis of this curve can generate beat-by-beat measurements of cardiac output/index, global end-diastolic volume, systemic vascular resistance index (SVRI), and extravascular lung volume (EVLV).[25] After structural regression analysis, the global end-diastolic volume converts to intra-thoracic blood volume (ITBV) index (ITBVI), which was found to be a better indicator of cardiac preload[26-28] compared to static indices obtained from a pulmonary artery catheter. Holm et al.[29] published the first and only randomized controlled, clinical trial comparing standard resuscitation to a goal-directed hyperdynamic resuscitation. The treatment protocol titrated fluid delivery to achieve an ITBV over 800 mL/m^2 and CI over 3.5 L/min/m^2. As expected, the protocol group received significantly more fluid than the control group. There were no statistically significant differences in mortality, ICU days, ventilator days, or organ dysfunction. Both groups demonstrated similar and predicable physiology during resuscitation, classically described as the "ebb and flow" phenomenon. The point of intersection between cardiac index and systemic vascular resistance (SVR) occurred earlier in the more aggressively resuscitated group, suggesting cardiac recovery is a function of volume loading. But even with aggressive volume repletion, most patients never reached a normal preload within the first 24 hours. This is, in part, due to

the profound increase in capillary permeability immediately post-injury and sensitivity to even small changes in hydrostatic pressure. Additionally, the initial hypodynamic state is disproportionately affected by cardiac dysfunction rather than by hypovolemia. With this trial, the concept of the hyperdynamic resuscitation slowly fell out of favor. Csontos et al.[30] randomized patients to a standard resuscitation guided by urine output and a protocol group that received an infusion titrated to maintain a narrow ITBVI margin of 800-850 ml/m^2. As expected, the protocol group received more fluid (mean of 5.7 cc/kg/TBSA, compared to 4.7 cc/kg/TBSA in the urine output group), but considerably less than published by Holms. This can be explained by their titration parameters. While both authors titrated an infusion rate to meet a minimum ITBVI of 800 ml/m^2, Holms only limited fluid if the extravascular lung water index (EVLWI) was beyond normal, which never occurred. While $S_{vc}O^2$ was higher in the aggressively resuscitated group indicating a more ideal oxygen delivery to consumption ratio, there was no significant difference in clinical outcomes between the two groups.

A critical look at these studies culminated in the 2008 American Burn Association (ABA) guidelines discouraging a preload-driven resuscitative strategy.[31] Research then shifted towards finding the minimal hemodynamic threshold required to still support end-organ function. Arlati et al.[32] proposed a resuscitative strategy referred to as "permissive hypovolemia". The study compared two matched cohorts. One group received fluid based on the Parkland formula, while the other group was resuscitated to maintain a CI of at least 2.2 l/min/m^2. Interestingly, the protocol group received significantly less fluid than predicted by Parkland while maintaining urine output over the 0.5cc/kg/hr threshold. Additionally, multi-organ dysfunction scores (MODS) were significantly lower in the protocol group. ITBV was found to range from 650 to 750 ml/m^2, well below what would be considered normal. From their data, the authors were able to demonstrate a positive curvilinear relationship between fluid delivery and organ dysfunction. Finally, the protocol group, despite receiving less fluid, did not demonstrate an altered hemodynamic pattern within the first 12 hours. Bak et al. sought to further clarify the correlation between hemodynamic parameters and traditional endpoints (UOP and mean arterial pressure) in patients with over 20% TBSA burns. Patients were resuscitated using Parkland formula to maintain a UOP of at least 0.5cc/kg/hr and a MAP of 70 mmHg. Hemodynamic indices obtained from TPTD, PAC, and transesophageal echocardiography (TEE) were recorded at 12, 24, and 36 hours, but not used as endpoints. They found good correlation in estimation of stroke volume between all three modalities. The mean amount of fluid administered was 4.02 cc/kg/hr for the cohort. As supported in previous studies, there was evidence of persistent hypovolemia at 12 hours that eventually resolved by 24 hours, despite adequate urine output.[33]

Sanchez et al.[34] performed a prospective cohort study using a similar "permissive hypovolemia" protocol with lower preload targets, but still using MAP and UOP. One-hundred and thirty-two patients (mean TBSA of 35%) were resuscitated to maintain UOP > 0.5 cc/kg/hr, CI > 2.5 l/min/m^2, ITBV > 600 ml/m^2, lactate < 2 and MAP > 65. The mean volume of fluid administered was 4.75 cc/kg/%TBSA, slightly higher than predicted. The authors observed initial hypovolemia after admission (as determined by ITBV) that normalized by 24 hours. In the setting of hypovolemia (ITBV < 800), the protocol was able to achieve an adequate CI and UOP, similar to the findings from Bak et al. There were significant correlations between changes in ITBV, CI and lactate clearance. There was no correlation between urine output and the TPTD-derived parameters. Based on their data, the authors found that hemodynamic monitoring led to changes in resuscitation in 34% of the cohort in the first 48 hours.

Echocardiography

Echocardiography, both trans-thoracic and transesophageal emerged as a dynamic assessment of both cardiac function and intravascular fluid status. As the ultrasound technology became smaller and more portable, its use in trauma became more defined. The FAST (focused assessment with sonography in trauma) was born out of a series of papers in

the early 1990s which found that a "positive test" was highly specific and sensitive for hemoperitineum and hemopericardium in blunt torso trauma.[35-38] The consensus at the end of that decade was that ultrasound should be a diagnostic adjunct as part of the trauma assessment. In the 2000s, the debate between invasive and noninvasive hemodynamic monitoring was in full force. Authors set out to streamline a complete transthoracic echocardiogram into an efficient, simple, and reproducible exam that surgeons and intensivists could perform. Several prospective studies demonstrated no significant difference between a cardiac and preload assessment using ultrasound compared to data retrieved from a pulmonary artery catheter in critically ill patients.[39] These exams made qualitative assessments of ventricular performance (hypodynamic, normal, and hyperdynamic) and size (reduced, normal, increased), ruled out presence of effusion, and estimated the patient's intravascular fluid status. Fluid status was estimated by measuring the inferior vena cava and observing variability with respiration. This technique was found to correlate well with loss of intravascular volume.[40-42] Ferrada et al.[43-46] published a series of papers investigating the use of an abbreviated exam to estimate fluid status and help guide therapy in hypotensive trauma patients still undergoing early resuscitation in the trauma bay. These exams assessed overall quality of contractility (good vs poor), determination of fluid status (full ventricles and full IVC versus hyperdynamic ventricles and flat IVC), as well as presence or absence of an effusion. The authors published their randomized controlled trial in 2014. The hypotensive trauma patients that were randomized to receive a focused ultrasound exam were given less fluid compared to the control arm. Additionally, time to the OR and time to ICU admission was statistically different between the groups.[46]

Several studies have shown that trans-esophageal echocardiography (TEE) is both safe and clinically useful in the burn population.[47-48] Etherington et al.[47] published a retrospective analysis of seventeen patients that underwent TEE during their hospitalization to better characterize indications and effect on management. They found that the primary indication for TEE was unexplained hypotension and bacteremia. When performed for hypotension, the most common finding was hypovolemia. Of note, TEE placement and interpretation was performed by trained anesthesiologists. There were no complications. The authors concluded that TEE is feasible and safe in burn patients and questioned its future use to help guide burn resuscitation. Only one study was found that evaluated the use of bedside TTE in burns. In the pediatric population, TTE tended to underestimate CO compared to transpulmonary thermodilution. The authors recognized that there are inherent challenges obtaining accurate measurements in the pediatric heart due to its smaller size and less pronounced borders.[49] There are no studies evaluating its use in an adult population.

The possibility of a TEE-guided resuscitation was first described by Wang et al. in a retrospective analysis of 21 patients.[50] The patients received fluid as predicted by the Chinese general formula. Hemodynamic endpoint obtained from a transesophageal echo-doppler were recorded hourly, to include aortic blood flow (ABF), CO, stroke volume (SV), maximal systolic acceleration (as a measure of contractility), and SVR. As anticipated, the authors observed CO and SVR trend towards normal by 24 hours post-burn. After performing linear regression, they found a much stronger correlation between cardiac output and contractility than between cardiac output and preload, again suggesting that the post-burn hypodynamic state is heavily weighted by myocardial depression, and to a lesser extent by preload reduction.

Held et al.[51] reported a retrospective analysis of 11 patients who were resuscitated with the addition of a 19F hemodynamic transesophageal echocardiogram (hTEE) (ClariTEE, Imacor Inc., Garden City, NY). Patients were included in the series if they had burns over 20% TBSA and mechanically ventilated. Unlike traditional TEE probes, these catheters are lower profile and can be left in for up to 72 hours. They provide continuous, real-time visualization and assessment of cardiac function and fluid status. All of the patients included were resuscitated using a standard TBSA-based formula and titrated based on urine output. The authors diagnosed some degree of cardiac dysfunction in seven of the eleven patients which led to earlier intervention with either vaso-

pressors or inotropes. Interestingly, they observed changes in cardiac performance before a change in urine output was evident. They noted an inverse relationship between ejection fraction (EF) and UOP. When EF was supratherapeutic (>75%), UOP fell below the desired range, but would improve when an intervention brought the EF closer to 65%. A supranormal LVEF would suggest a hyperkinetic state which is often seen in the latter half of large burn resuscitations. The exact reason is probably multifactorial, effected by vasoplegia, hyperadrenergic drive, and ongoing hypovolemia – contractility, preload, and afterload. The same findings have been observed in patients with sepsis; patients with hyperdynamic LVEF (EF >70%) had lower UOP and higher rates of renal replacement therapy compared to those with a normal or depressed EF.[52]

Arterial waveform analysis

More recently, the use of arterial wave form analysis for hemodynamic monitoring has been investigated (FloTrac/Vigileo, Edwards LifeScience). These devices generate beat-to-beat measurements of cardiac output and estimations of preload and preload responsiveness based on waveform variability.[53-54] In mechanically ventilated patients, the increase in intra-thoracic pressure with inhalation causes a transient decrease in preload and stroke volume. With arterial waveform analysis, these small variations can be mapped over time, making it an attractive alternative to static preload indicators such as CVP or PAWP. Pulse pressure variation (PPV) and stroke volume variation (SSV) were studied by Lavrenitieva et al. as a marker of fluid responsiveness and endpoint in burn resuscitation.[53] In search of a meaningful correlation, the authors used a femoral arterial line to obtain parameters from both waveform analysis and transpulmonary thermodilution. For their resuscitation, the goal was to maintain an ITBV of 800-850 (ml/m^2) and CI greater than 3.5 l/min/m^2. The design was prospective and observational. The mean TBSA was 39% and mean fluid delivered was 5.7 cc/kg/%TBSA. Despite a higher than predicted volume of fluid given, the CI and ITBV goals were not reached within the first 16 hours, similar to findings by Bak et al. Urine output was also higher than recommended (2.1 cc/kg/hr), also similar to other ITBV-guided protocols previously discussed. The authors were able to show a statistically significant correlation between CI and SVV.[53]

The idea of using waveform variations as a surrogate for preload responsiveness is a relatively new one. In 2018, Chaio et al. published a retrospective cohort analysis of 13 severely burned patients with a mean TBSA of 68%, all with inhalation injury.[55] All patients were mechanically ventilated and resuscitated as predicted by Parkland. The goals were to maintain urine output between 30-50 cc/hr, a CI > 2.5 ml.min/m^2, and an SVV < 12%. Additional fluid was administered or inotropes given depending on which parameters were not being met. Colloid or FFP "rescue therapy" was held until 12 hours post-burn. Despite the severity of burns, fluid administered in the first 24 hours was less than predicted by Parkland (3.62 cc/kg/hr). All patients reached the established hemodynamic goals by 32 hours. One patient developed ARDS, but there was no incidence of acute renal failure or death at one week. The data was limited by sample size and its retrospective nature, however the results were notable since massively burned patients with inhalation injury typically require fluid in excess of predictive formulas and often fail resuscitative attempts. The results could be explained, at least in part, by the young age of the cohort (mean age of 21 years).

In a porcine model, animals were randomized to either no resuscitation, resuscitation guided by a clinical decision support tool, or a higher-then-predicted resuscitation.[56] All swine were mechanically ventilated and sustained 40% TBSA thermal burns. The authors sought to establish a correlation between pulse waveform analysis (PWA) derived variables (pulse pressure variation and systolic pressure variation) and urine output in both normal and extreme resuscitative models. Multiple CO indices were tested and correlated against a reference CO obtained via thermodilution technique. The performance of PWA-derived CO, SV and UOP were compared to reference CO and SV. The author's analysis generated some interesting results. Statistical testing demonstrated comparable accuracy for PWA-derived indices and UOP in both under and over-resuscitation, however there was less agreement

within the normal resuscitative model. After regression analysis, PPV and SPV was a better performing indicator of reference SV, but UOP was a better indicator of CO. PWA-derived indices performed best when calibrated to the individual subject, however these correlations were preserved even when subject-specific calibrations were removed. Further, in a "normal resuscitation", they noted that the UOP normalized 2 hours after SV and CO normalized, supporting a possible lag effect. The authors concluded that PWA-derived endpoints may serve a complimentary purpose and provide additional information when used in conjunction with urine output.

Compensatory reserve measurement

An emerging concept, the "compensatory reserve", is a physiological phenomenon that was conceived and published nearly a decade ago.[57-58] The compensatory reserve measurement (CRM) is based on the principle that compensatory mechanisms are integrated in totality and represented by features of the ejected and reflected arterial waveforms and photoplethysmography (PPG) waveforms. CRM utilizes a deep learning convolutional neural network, to monitor and assess the characteristics of the arterial waveform or photoplethysmography to detect subtle waveform changes and predict patient decline into a shock state.[57] In a recent study, a measured reduction in CRM by 35% indicated the onset of sepsis approximately one day prior to culture positivity.[59] Studies regarding the use of CRM in various shock states are ongoing.

Lessons learned

The search to clearly define an adequate resuscitation is far from over, however the last forty years have provided some very important lessons:

No amount of volume replacement will overcome the massive fluid loss and profound cardiac depression observed in burn shock. A completely preload-dependent resuscitative strategy will lead to over-resuscitation.

Attempting to push burn physiology to a hyperdynamic state by aggressive volume loading does little to attenuate the effects of burn shock and will often lead to over-resuscitation.

There is a clear relationship between over-resuscitation and organ dysfunction.

Areas of future research

Urine output is still the most commonly used endpoint to guide burn resuscitation. Multiple studies have found that even in a state of hypovolemia, urine output will still be "adequate". This suggests that there is perhaps a minimal cardiac output threshold required to support end-organ perfusion. Since cardiac output is the total measure of cardiovascular efficiency, it accounts for the complex interplay between preload, contractility, and afterload. When hemodynamic monitoring is employed for difficult or challenging resuscitations, there may be a role for maintaining a minimal cardiac index above 2-2.5 $l/m/m^2$ by either volume loading or direct cardiac support. Future protocols should seek to clarify this threshold.

Multiple attempts to normalize preload using both pressure and volume-based parameters resulted in over-resuscitation with no clinical improvement. Fluid responsiveness, or the transient increase in stroke volume in response to fluid, may be more clinically useful in this population. These parameters show early promise and may allow for earlier intervention before changes in urine output are observed. Further studies should attempt to clarify the relationship between PPV and SSV and urine output.

Burn resuscitation is anything but predictable. Injury and patient-related factors make each resuscitation unique, and the paradigm is slowly moving away from a "one size fits all" approach to a more individualized approach. Burn patients will continue to get older, with more and more renal and cardiovascular diseases. The art and science of the burn resuscitation should continue to evolve with the population. An individualized strategy will undoubtedly require more precise information to make decisions regarding fluid delivery.

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