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CENTRAL VENOUS PRESSURE VS PULMONARY ARTERY CATHETER DIRECTED SHOCK RESUSCITATION

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Abstract

Previously, we developed a protocol for shock resuscitation of severe trauma patients to reverse shock and regain hemodynamic stability during the first 24 ICU hours. Key hemodynamic measurements of cardiac output and preload were obtained using a pulmonary artery catheter (PAC). As an alternative, we developed a protocol that used central venous pressure (CVP) to guide decision making for interventions to regain hemodynamic stability (MAP ≥ 65 mmHg and HR ≤ 130 bpm). Either protocol was available and required for traumatic shock resuscitation using bedside computerized clinical decision support to standardize decision making, and PAC was available if CVP directed resuscitation was inadequate. We hypothesized that patients would be appropriately assigned to either protocol by trauma surgeon assessment of hemodynamic stability upon intensive care unit (ICU) admit. High risk patients admitted to a Level 1 trauma center ICU underwent resuscitation. Criteria were: 1) major torso trauma, 2) base deficit (BD) ≥ 6 mEq/L or systolic blood pressure < 90 mmHg, 3) transfusion of ≥1 unit packed red blood cells (PRBC), or age ≥ 65 years with two of three criteria. Patients with brain injury were excluded. Data were recorded prospectively. In 24 months ending 7/31/06, of 193 patients, 114 (59%) were assigned CVP and 79 (41%) PAC directed resuscitation. A subgroup of 11 (10%) initially assigned CVP was reassigned PAC directed resuscitation (7±2 hr after start) due to hemodynamic instability. Crystalloid fluid and PRBC resuscitation volumes for PAC (8±1 L LR, 5±0.4 units PRBC) were greater than CVP (5±0.4 L LR, 3±0.3 unit PRBC) and similar to CVP – PAC protocol subgroup patients (9±2 L LR, 5±1 units PRBC). ICU stay and survival rate for PAC (18±2 dy, 75%) were similar to CVP – PAC (17±4 dy, 73%) and worse than CVP protocol subgroup patients (9±1 dy, 98%). Traumatic shock resuscitation is feasible using CVP as a primary hemodynamic monitor as part of a protocol that includes explicit definition of hemodynamic instability and where PAC monitoring is readily available. Computerized decision

support provides a technique to implement complex protocol care processes and analyze patient response.

Key words: shock resuscitation, trauma, computerized clinical decision support, standardized decision making, computerized protocol

INTRODUCTION

We have reported development and use of a computerized protocol for shock resuscitation of severe trauma patients.(17-20, 22) This protocol was developed to reverse traumatic shock associated with hemorrhage, and to maintain hemodynamic stability during the 1st 24 ICU hours. Use of this protocol, implemented using computerized bedside decision support, was a key part of early ICU care for patients meeting injury and shock severity criteria during their 1st ICU day at a busy Level 1 trauma center, and provided the opportunity to review and refine protocol performance.(22) Key hemodynamic measurements were obtained using a pulmonary artery catheter (PAC). These include cardiac output and pulmonary capillary wedge pressure. Although providing the most direct monitor of hemodynamic function, use of the PAC has been controversial.(4, 5) As an alternative to this PAC protocol, we developed a resuscitation protocol that used central venous pressure (CVP) to monitor hemodynamic stability and to guide decision making for shock resuscitation.(24)

Both protocols were implemented using bedside computerized clinical decision support,(9, 12, 21, 22, 27-30, 38) and either protocol was available and required to guide decision making for trauma shock resuscitation. We report comparison of these shock resuscitation protocols. For this study, we hypothesized that patients would be appropriately assigned to either resuscitation protocol based on trauma surgeon assessment of hemodynamic stability at the time of intensive care unit (ICU) admission.

MATERIALS AND METHODS

High risk patients who were admitted to the Shock Trauma ICU at Memorial Hermann Hospital (MHH; a Level 1 regional trauma center serving SE Texas and a population of ~4 million) and who met specific criteria underwent a 24 hour shock resuscitation process implemented using computerized bedside decision support to standardize decision making for this aspect of care. The shock resuscitation patients were those who had incurred major torso trauma and arrived in the Emergency Department (ED) with ongoing hemorrhage, hypotension or metabolic stress, and who survived to be admitted to the ICU.

During this study, criteria for the resuscitation protocol were:(24-26) 1) major torso trauma, defined as injury of ≥2 abdominal organs, ≥2 long bone fractures, complex pelvic fracture, flail chest, or major vascular injury, 2) metabolic stress, defined as base deficit (BD) ≥ 6 mEq/L within 12 hours of hospital admission, and / or hypotension, defined as SBP < 90 mmHg documented in the ED, 3) transfusion of ≥1 unit packed red blood cells (PRBC), or age ≥ 65 years with any two of the three previous criteria. Patients with these criteria who also incurred severe brain injury, defined as Glasgow Coma Scale score ≤ 8 in the ICU and abnormal brain computed tomography (CT) scan finding, were not resuscitated by this standardized protocol, unless the patient's brain injury was assessed by the attending neurosurgeon to be at low risk of worsening cerebral edema with crystalloid fluid volume loading.

A protocol based on maintenance of oxygen delivery index (DO_2I) ≥ a specific goal to maintain hemodynamic stability was described previously.(17-20, 22, 23, 38) Figure 1a provides a summary of this protocol described as a stepwise logical decision process. Hemoglobin concentration ([Hb]) was monitored at bedside using a point of care analyzer. [Hb], cardiac index

(CI), and pulmonary capillary wedge pressure (PCWP) were the key measurement variables that were used to guide protocol logic. Referring to Figure 1a, with this protocol, upon ICU admission, a PAC with continuous cardiac output (CCO) monitoring capability and an arterial catheter were placed (A). The protocol logic directed maintenance of $DO_2I \geq 500$ mL O_2/min-m^2 (B) with interventions of: PRBC if [Hb] < 10 g/dL and $DO_2I < 500$ mL O_2/min-m^2; crystalloid fluid bolus (LR, 1 L) if [Hb] ≥ 10 g/dL, PCWP < 15 mmHg, and $DO_2I < 500$ mL O_2/min-m^2 (C); PCWP – CI optimization ('Starling curve') if [Hb] ≥ 10 g/dL, PCWP ≥ 15 mmHg and $DO_2I <$ 500 mL O_2/min-m^2 (D); inotrope infusion (milrinone or dobutamine) if PCWP – CI was optimized, [Hb] ≥ 10 g/dL, PCWP ≥ 15 mmHg and $DO_2I < 500$ mL O_2/min-m^2; and, vasopressor infusion (norepinephrine) if inotrope infusion was ongoing, PCWP – CI was optimized, [Hb] ≥ 10 g/dL, PCWP ≥ 15 mmHg, $DO_2I < 500$ mL O_2/min-m^2 and MAP < 60 mmHg (E).

An alternative protocol based on maintenance of CVP greater than or equal to a specific goal to maintain hemodynamic stability is summarized in Figure 1b. As a component of CVP protocol logic, hemodynamic stability was defined as MAP ≥ 65 mmHg and HR ≤ 130 bpm. CVP, [Hb], MAP and HR were the key measurement variables that were used to guide protocol logic. Referring to Figure 1b, depending upon shock status assessment by the attending trauma surgeon and assignment of CVP or PAC directed resuscitation protocol, upon ICU admission, a central venous line (subclavian or internal jugular) and an arterial line were placed (A). If CVP ≥ 20 mmHg was measured and cardiogenic shock was suspected, or if resuscitation had been ongoing for 24 hr, then the CVP protocol was not continued (B). If CVP ≤ 5 mmHg or [Hb] < 9 g/dL was measured (E), or if hemodynamic instability (defined as MAP < 65 mmHg or HR > 130 bpm) was detected (D), then the protocol logic directed maintenance of CVP ≥ 10 mmHg and [Hb] ≥

10 g/dL with interventions of: crystalloid fluid bolus (LR, ≤3 L) if CVP < 10 mmHg and / or PRBC (≤2 units) if [Hb] < 10 g/dL and CVP < 10mmHg) (F). If hemodynamic instability persisted with 10 ≤ CVP ≤ 15 mmHg, then increase and maintenance of CVP ≥ 15 mmHg and [Hb] ≥ 10 g/dL with those same interventions was directed (C). If hemodynamic instability persisted with CVP ≥ 15 mmHg, then change to the PAC protocol for the remainder of the 1st 24 ICU hours was directed (G).

These protocols directed standardized decision making for shock resuscitation during the 1st ICU day. The protocols were developed and described in detail using conventional logic flow (decision tree) diagrams, which are summarized in Figure 1. This process involved iterative modification by trauma team group consensus and, initially, test at bedside as 'paper protocols'. (38) The resulting logic was computerized and the protocols were implemented using interactive computer applications to guide decision support at bedside. The PAC protocol, developed ~1997-2000, was implemented as a computer application in February 2001, and the CVP protocol, developed ~2002-2004, was implemented as a computer application in August 2004. For this study, the protocols were combined in a single bedside computer application that required entry of basic demographics, injury and shock severity criteria, and current clinical chemistry and blood and fluid input - output (I/O) data, and then requested the attending trauma surgeon to select either CVP or PAC directed resuscitation based on that current assessment.

At the start of the shock resuscitation protocol, arterial blood gas (ABG), and ICU blood chemistry and coagulation profiles were obtained and repeated every 4 hours, or as needed, for the duration of the 24 hour process. Data from the bedside protocol computer, nursing flow sheet vital signs, input – output volumes and clinical chemistry, and data characterizing the pre ICU

course were recorded in a Trauma Research Database. The Trauma Research Database was maintained with approval of the Committee for the Protection of Human Subjects (Institutional Review Board) of the University of Texas Health Science Center at Houston.

Data describing the patients' resuscitation process and clinical course were obtained prospectively from computerized protocol interaction at bedside. When the bedside nurse or physician entered specific clinical laboratory or physiologic monitor measurements requested as part of protocol logic, these data were compared with thresholds for intervention and the most recent data, and were displayed (with measurement time) for ongoing reference of the patient's resuscitation status. Based on threshold comparison, protocol logic instructed a specific intervention, or no intervention and continued monitoring (with a maximum time for repeated check of patient status). If a specific intervention was instructed, that intervention required physician review, and the protocol application requested acknowledgment of its completion. The shock resuscitation process was ongoing for 24 hours from its start time (specified), and this time 'clock' was part of the protocol logic. After 24 hours, the protocol application either terminated or, if an intervention or data entry was pending, requested that the bedside clinician terminate the protocol after their completion.

Data are presented as mean ± sem in text, tables and figures. Data were analyzed using X^2 tests to compare non parametric data and analysis of variance to detect changes of continuous variables with time or to compare more than two groups of a specific variable.

RESULTS

During 24 mo ending 07/31/2006, 193 patients met criteria and received shock resuscitation using the CVP or PAC protocol processes described above. As a group, these patients had severe shock in the emergency department (BD ED = 8 ± 1 mEq/L) and required massive transfusion (10 ± 1 unit PRBC) pre ICU. Initial protocol assignment, determined by the attending trauma surgeon at the time of ICU admission, was more frequent for CVP directed protocols: 114 (59%) patients were initially assigned to the CVP protocol (CVP protocol subgroup), and 79 (41%) were initially assigned to the PAC protocol (PAC protocol subgroup). Eleven patients (10%) initially assigned to the CVP directed protocol progressed to be reassigned to PAC directed resuscitation during the 1st 24 ICU hours (CVP – PAC protocol subgroup). Mean time of start of the PAC directed protocol for this CVP – PAC protocol subgroup was 7 ± 2 hr after start of the initially assigned CVP directed protocol.

Table 1 summarizes demographics of the CVP (not reassigned), PAC (initially assigned), and CVP – PAC protocol subgroups. Age and gender were similar for each subgroup. Compared with PAC and CVP – PAC subgroups, the CVP subgroup comprised fewer patients with blunt mechanism of injury. Injury severity score (ISS) tended to be less for the CVP than for the other subgroups, and was equal for PAC and the CVP – PAC subgroups. Mean BD in the ED upon hospital admission for the CVP protocol subgroup was less than that of the PAC and CVP – PAC protocol subgroups. Mean BD in the ED upon hospital admission was equal for the PAC and CVP – PAC protocol subgroups. Crystalloid volumes administered before ICU admission were similar for subgroups. PRBC volumes administered before ICU admission were less for the CVP than the PAC protocol subgroup patients, but not significantly less than for the CVP – PAC subgroup patients. Compared to the PAC subgroup, mean BD upon ICU admission was less for

the CVP subgroup (not reassigned). During ICU resuscitation, CVP protocol subgroup patients received less crystalloid fluid and PRBC volume intervention than the PAC (initially assigned) or CVP – PAC subgroup patients. Throughout ICU resuscitation, mean crystalloid fluid volume for the CVP-PAC subgroup tended to exceed that of the PAC (initially assigned) subgroup. Mean duration of ICU stay for the PAC and CVP – PAC protocol subgroups was nearly twice that of the CVP protocol subgroup. The PAC (initially assigned) and CVP – PAC protocol subgroups had equivalent survival rates that were much less than that of the CVP protocol subgroup.

Figure 2a shows protocol directed cumulative crystalloid fluid infusion volumes during ICU resuscitation for CVP (not reassigned), PAC (initially assigned) and CVP - PAC protocol subgroups. Cumulative crystalloid fluid volumes for CVP protocol subgroup patients were less than those required by the PAC protocol subgroup patients to attain and maintain protocol hemodynamic performance goals. Shown in Figure 2b, mean PRBC transfusion volumes for CVP protocol subgroup patients were ~50% those for PAC protocol subgroup patients. Crystalloid fluid and PRBC volumes for PAC (initially assigned) and CVP – PAC protocol subgroups were similar.

Protocol performance is summarized in Figure 3. Central venous and pulmonary capillary wedge pressures for CVP (not reassigned), PAC (initially assigned) and CVP – PAC protocol subgroups during ICU resuscitation, with protocol directed goals (as needed for individual patients), are shown in Figure 3a. For the CVP – PAC protocol subgroup, transition from CVP to PCWP performance goal is indicated at hour 7. For the CVP protocol subgroup, mean CVP ~ 10 mmHg (protocol goal) was attained 8 hr after protocol start, and was maintained throughout the

remaining resuscitation time. For the PAC protocol subgroup, $10 \leq PCWP \leq 15$ mmHg was maintained for ~14 hours after protocol start, and exceeded 15 mmHg after that time. PAC protocol directed PCWP was greater than CVP protocol directed CVP. For the CVP – PAC protocol subgroup, during the 1st 6 ICU hours, CVP exceeded that for the CVP (not reassigned) protocol subgroup. For this subgroup, the PAC directed protocol was started 7 ± 2 hr after start of initially assigned CVP resuscitation, and, from that time throughout the remaining resuscitation process, PCWP exceeded that for the PAC protocol subgroup (initially assigned). Shown in Figure 3b, for both CVP and PAC protocol subgroups, mean [Hb] ~ 11 g/dL exceeded CVP and PAC protocol goals ([Hb] ≥ 10 g/dL), and was maintained throughout ICU day 1 with slight, but significant, variation for the CVP and PAC protocol subgroups. For the CVP – PAC protocol subgroup, greater, but insignificant, variation occurred, with decrease from mean [Hb] ~ 11.6 to ~9.1 g/dL in the initial 4 hours and correction to mean [Hb] > 10 with decision to change from CVP to PAC protocol.

Hemodynamic stability during ICU day 1 is summarized in Figure 4. Maintained throughout ICU resuscitation, mean MAP ~ 92 mmHg for the CVP protocol subgroup exceeded mean MAP ~ 85 mmHg for the PAC protocol subgroup. (See Figure 4a.) For the CVP – PAC protocol subgroup (n = 11), mean MAP decreased during the 1st 4 hr of ICU resuscitation, and then recovered to a course indistinguishable from the PAC protocol subgroup. Maintained throughout ICU resuscitation, mean HR ~ 106 bpm for the CVP protocol subgroup was less than mean HR ~ 116 bpm for the PAC protocol subgroup. (See Figure 4b.) For this CVP – PAC protocol subgroup, HR was similar to the PAC protocol subgroup. For 6 (55%) of these patients, hemodynamic stability was inadequate according to the agreed definition for the CVP protocol (i.e. MAP ≥ 65

mmHg or HR ≤ 130 bpm), and hemodynamic instability persisted for >3 hr for 8 (73%) of these patients during the 1st 8 hr of resuscitation.

PCWP – CI optimization (i.e. 'Starling Curve' intervention to incrementally increase CI and DO_2I with successive bolus crystalloid infusions) occurred with 23 patients, including 4 of the CVP – PAC protocol subgroup. Use of vasopressor and / or inotrope agents occurred in 13 PAC, 3 CVP and 3 CVP – PAC protocol subgroup patients. The PAC protocol incorporated administration of an inotrope agent (milrinone or dobutamine) and a vasopressor agent (norepinephrine) as needed as part of protocol logic, and PAC protocol directed use of inotrope (n = 5) and vasopressor (n = 5) agents occurred rarely. Use of these agents was not a part of CVP protocol logic, and a vasopressor agent (vasopressin, n = 2; norepinephrine, n = 1) and an inotrope agent (epinephrine; n = 1) were therefore used rarely in addition to protocol directed resuscitation. For CVP – PAC protocol subgroup patients, a vasopressor agent (vasopressin; n = 2) and an inotrope agent (epinephrine; n = 1) were used rarely in addition to protocol directed resuscitation.

Metabolic indicators of response to ongoing resuscitation are shown in Figure 5. Shown in Figures 5a and b, BD and blood lactate concentration ([lactate]) were greater at start and throughout ICU resuscitation for the PAC compared to CVP protocol subgroup patients. For both CVP and PAC protocol subgroups, mean BD decreased to near normal range during the 1st 8 hr of ICU resuscitation, and remained stable. For the CVP – PAC protocol subgroup patients (n = 11), BD at start of ICU resuscitation was similar to that of the PAC subgroup and tended to be greater than that of the CVP protocol subgroup. During resuscitation, a combination of CVP and PAC protocols, mean BD remained similar to that of the PAC protocol subgroup, and was

greater than that of the CVP protocol subgroup. Mean [lactate] decreased throughout ICU resuscitation for both CVP and PAC protocol subgroups. Mean [lactate] was nearly indistinguishable for PAC and CVP – PAC protocol subgroups, except at 4 hr, the approximate time of death for one patient of the CVP – PAC protocol subgroup.

DISCUSSION

Shock resuscitation is necessary and life saving for most patients who have incurred severe injury and blood loss. Strategies for shock resuscitation include replacement of lost blood volume and hemoglobin to regain and maintain adequate blood pressure, urine output, arterial or mixed venous hemoglobin O_2 saturation, CVP, or DO_2.(6-8, 13-15, 31, 32, 34-37, 39-42) These strategies vary among trauma centers and trauma surgeons, and limited data exist to demonstrate superior efficacy of any process.

From 1998-2004, we focused on a protocol using DO_2 as a resuscitation hemodynamic performance goal / endpoint, because it was a strategy with demonstrated feasibility in this most severely injured and hemodynamically unstable patient population,(17, 33, 36, 37, 40) and because it is the only strategy that has been subjected to prospective clinical trial.(2, 3, 10, 11, 35) With controversy about the PAC,(4, 5) and, more recently, aggressive volume loading with crystalloid fluid,(1) we examined alternatives. The purpose of this study was to compare the performance of a CVP directed resuscitation protocol based on measurements of CVP and [Hb] with that of the previously implemented PAC directed protocol based on measurements of DO_2.

CVP and PAC protocols were each developed as a set of rules in a sequence to logically describe the process of care for shock resuscitation and to provide a standardized decision making process for bedside clinicians, specifically to regain and maintain hemodynamic stability through ICU day 1. Thresholds for interventions were specified for those variables identified to be key indicators of hemodynamic function, accurately, easily and repeatedly measured, and directly affected by standard interventions.(27, 29)

The CVP subgroup patients were more hemodynamically stable than the PAC subgroup patients throughout respective shock resuscitation processes, consistent with less severe injury and/or shock. (See Figure 4 and Table 1.) For the CVP subgroup, MAP was greater and HR was less than for the PAC subgroup. These differences between subgroups are an indication that the protocol assignment at time of ICU admission, CVP or PAC directed, was usually appropriate. Most patients for whom CVP directed shock resuscitation was selected were hemodynamically stable and did not have severe ongoing blood loss after surgical or interventional radiological procedures, but, due to severe injury or shock pre ICU, were judged to require a continued monitoring and resuscitation intensity during ICU day 1 that was consistent with the CVP protocol process. The patients for whom PAC directed shock resuscitation was selected were hemodynamically unstable or had severe ongoing blood loss after pre ICU procedures. For this subgroup, at the time of protocol start, MAP = 85 ± 3 mmHg and HR = 115 ± 3 bpm. Pre ICU, these patients received 15 ± 2 units PRBC and 6 ± 1 L crystalloid fluid. These patients were judged to require ongoing shock resuscitation and maximal hemodynamic monitoring intensity in the ICU provided by the PAC protocol process. Interventions directed by the respective protocols and executed by bedside clinicians were also consistent with these observations.

As designed, for the CVP subgroup, mean CVP ~ 10 mmHg was gradually attained over the 1st 8 hours, and was uniformly maintained for the duration of the protocol. For the PAC subgroup, the time course of mean PCWP was similar to that reported previously using this protocol, and reflected cardiac preload greater than that for the CVP subgroup. (See Figure 3a.) Mean [Hb] ~ 11 g/dL was maintained for both subgroups, and had a time course of remarkable stability similar to that for our previously reported PAC protocol studies.(16-19) Mean [Hb] for the CVP – PAC

subgroup decreased rapidly during the 1st 4 ICU hours, possibly reflecting unappreciated ongoing blood loss from several patients in this subgroup. (See Figure 3b.)

During this study, transition from CVP to PAC directed resuscitation was recommended for 11 of 114 patients (10%) initially assigned to receive CVP directed shock resuscitation, but for whom PAC directed resuscitation was later necessary. Persistent hemodynamic instability (i.e. MAP < 65 or HR > 130) prompted protocol instructions for repeated crystalloid (LR) infusions (cumulative volume 5 ± 1 L during 1st 7 hr) to obtain CVP ≥ 15 mmHg (17 ± 2 mmHg after 7 hr of resuscitation), and prompted protocol recommendation for change to the PAC directed protocol. (See Figure 1b.) Figure 4a depicts rapidly deteriorating hemodynamic stability (indicated by mean MAP) for this subgroup during the 1st 4 hr of CVP directed resuscitation, and recovery to that of the PAC subgroup with decision for transition to the PAC protocol, for which a PAC was functional 7 ± 2 hr after start of resuscitation. After protocol transition, mean PCWP of the CVP – PAC subgroup exceeded that of the PAC (initially assigned) protocol subgroup, possibly reflecting initial CVP protocol directed preload, ongoing shock and hemodynamic instability. The patients in this CVP – PAC subgroup were among the most severely injured, and upon arrival in the ED, had severe shock, indicated by initial BD obtained in the ED that was similar to those patients who were assigned PAC directed shock resuscitation upon ICU admit and greater than that of the CVP subgroup ($p < 0.05$). Pre ICU interventions for the CVP – PAC subgroup patients included crystalloid fluid volumes (6 ± 2 L) similar to those for the PAC subgroup patients, but PRBC volumes (9 ± 2 unit) similar to those for the CVP subgroup patients, suggesting early control of hemorrhage. Mean BD during ICU resuscitation for this CVP – PAC subgroup compared closely with the PAC subgroup; mean [lactate] was nearly

identical. Duration of ICU stay and rate of survival for the CVP – PAC and PAC subgroups were very similar.

The protocol assignments made at the time of ICU admission may have been made according to apparent signs of minimal ongoing blood loss, and, for most trauma surgeon team members, preference to avoid placement of a PAC. In retrospect, these patients were incorrectly assigned ('mistriaged') to a resuscitation protocol process that did not provide adequate hemodynamic monitoring. Assignment of patients to either protocol based on earliest ED indication of severe injury and shock, instead of indications at time of ICU admit, may have prompted PAC protocol assignment for these patients. This was a change implemented in ongoing quality improvement efforts during 2005-2006. Effect of this change on the balance of CVP vs PAC protocol assignment remains to be seen.

CVP directed resuscitation, with minimal hemodynamic insight compared to presumptive PAC monitoring, is a departure from maximal hemodynamic monitoring for the high risk major torso trauma population. Undertaken as a 'proof of concept' in the MHH Shock Trauma ICU, where immediate access to PAC and other intensive monitoring was available, the CVP directed resuscitation process seemed safe and reliable in the hands of experienced trauma surgeons and bedside ICU nurses. The availability of either CVP or PAC directed resuscitation protocols as bedside computerized clinical decision support tools to standardize decision making was an attractive option for the trauma surgeon team. The selection of either protocol at time of ICU admit was left to the judgment of the admitting trauma surgeon, and nearly equal assignment to CVP and PAC protocols was found after 1 year (2004 – 2005: CVP protocol assignment n= 60 (57%); PAC protocol assignment n= 46 (43%)) and slight tendency toward more CVP protocol

assignment during year 2 (2005-2006: CVP protocol assignment n= 54 (62%); PAC protocol assignment n= 33 (38%)). Whereas the PAC protocol process was well proven in the MHH Shock Trauma ICU, the CVP process was not, and its implementation was initially expected to require ongoing modification. This was not found to be necessary, possibly due to extensive experience with thresholds for intervention that were incorporated in the protocols, e.g. CVP ≥ 10 mmHg, CVP ≥ 15 mmHg, PCWP ≥ 15 mmHg, and [Hb] ≥ 10 g/dL.

The CVP resuscitation process was initially conceived as a process to be implemented in the ED and to proceed throughout crucial pre ICU hours to obtain controlled, safe resuscitation for trauma patients, and was proposed as part of the NIGMS sponsored 'Glue Grant' (Inflammation and the Host Response to Injury, RG Tompkins MD ScD, PI; Patient Oriented Research Core, RV Maier MD, Chair, Patient Oriented Research Core; National Institute for General Medical Sciences, Washington DC, U4 GM62119; www.gluegrant.org). Of note, the Glue Grant consensus group process successfully identified issues of concern and elicited a CVP directed guideline process for shock resuscitation beginning in the ED and continuing through ICU day 1 that was published as a clinically current standard of care.(24) We report verification of a more explicit care process based on this Glue Grant guideline that was able to be replicated among severely injured patients and was found to be functional in an ICU setting where additional monitors, procedures and personnel are typically available. Also of note, implementation of the CVP directed resuscitation process described in this report was not accomplished in the MHH ED, due to inability to reliably obtain central line placement or CVP measurement in patients in that often chaotic setting. Whether this CVP directed resuscitation process is feasible as an explicit computerized protocol or as a less specific guideline in ED settings of busy (Level 1) trauma centers remains to be reported by Glue Grant investigators.

Results of this analysis of PAC and CVP directed shock resuscitation protocol use and performance at a busy Level 1 regional trauma center indicates that appropriate assignment to either protocol by experienced trauma surgeons based on assessment of shock status at time of ICU admission was usually correct, but incorrect in ~10% of cases. To compensate for inappropriate assignment, the ability to rapidly detect hemodynamic instability, defined explicitly and specifically, and to change resuscitation process to incorporate more intensive hemodynamic monitoring and intervention, provided by a PAC and associated protocol logic, may have prevented early death of most of the CVP – PAC protocol subgroup patients. Although injury severity by retrospective ISS or prospective trauma surgeon vital signs assessment may not distinguish potential survivability, pre ICU BD or need for massive transfusion may indicate need for hemodynamic monitoring and intervention during ICU resuscitation guided by a PAC. Benefit from initial assignment to PAC resuscitation, more intensive hemodynamic monitoring and interventions (preload optimization, vasopressor, inotrope therapies) than provided with the CVP protocol, is not able to be determined from the data obtained. Bedside computerized clinical decision support tools were used to detect hemodynamic instability with the CVP protocol process, to prompt change to the PAC protocol process, and to guide intervention to correct the instability. The PAC was a necessary resource for this resuscitation process, and continued to provide the most direct hemodynamic monitoring technology currently available. The CVP and PAC shock resuscitation protocols were developed through extensive consensus deliberation and logical process derivation to be replicable among patients and to direct decision making and practical ICU workflow. These protocol processes were found to function reliably in a busy shock trauma ICU. Derived from best evidence and expert opinion, they are designed for continued development and refinement based on ongoing experience. Computerized clinical

decision support technology continues to provide a technique to implement complex protocol care processes and to determine how patients respond to standardized decision making for specific aspects of care.(38)

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Table 1. Demographic descriptions and intervention summaries for patient subgroups who received CVP, PAC, and CVP to PAC directed shock resuscitation during ICU day 1 using computerized bedside decision support tools to standardize clinical decision making.

[a, b] p<0.05, anova	CVP	PAC	CVP→PAC
n	103	79	11
age (yr)	39 ± 1	37 ± 2	46 ± 4
gender (% male)	72	77	82
blunt mech (%)	75 [a]	84 [b]	91 [b]
ISS	24 ± 1	28 ± 1	28 ± 3
BD ED (mEq/L)	7 ± 1 [a]	10 ± 1 [b]	9 ± 1 [b]
crys pre ICU (L)	5 ± 0.4	6 ± 1	6 ± 2
PRBC pre ICU (unit)	7 ± 1 [a]	15 ± 2 [b]	9 ± 2
BD ICU t=0 (mEq/L)	4 ± 0.4 [a]	6 ± 1 [b]	6 ± 1
ICU crys resus (L)	5 ± 0.4 [a]	8 ± 1 [b]	9 ± 2 [b]
ICU PRBC resus (unit)	3 ± 0.3 [a]	5 ± 0.4 [b]	5 ± 1 [b]
ICU stay (dy)	9 ± 1 [a]	18 ± 2 [b]	17 ± 4 [b]
survival (%)	98 [a]	75 [b]	73 [b]

Figure captions

Figure 1. Logic flow diagrams depicting summaries of:

a. Pulmonary artery catheter (PAC) directed protocol: Maintains $DO_2I \geq 500$ mL O_2/min-m^2, [Hb] ≥ 10 g/dL. Preload (PCWP) increase is indicated if: non responder to volume load or Hb replacement. Inotrope / vasopressor support is indicated if: hemodynamic instability with PCWP ≥ 15 mmHg, [Hb] ≥ 10 g/dL, and PCWP – CI optimized. (See text for explanation of A, B, C, D.)

b. Central venous pressure directed (CVP) protocol: Maintains CVP ≥ 10 mmHg, [Hb] ≥ 10 g/dL. CVP increase is indicated if: CVP ≤ 5 mmHg or [Hb] < 9 g/dL; hemodynamic instability (MAP < 65 mmHg or HR > 130 bpm) persists with CVP ≥ 10 mmHg and [Hb] ≥ 10 g/dL. Transition to PAC protocol is indicated if: severe or worsening shock status; hemodynamic instability with CVP ≥ 15 mmHg and [Hb] ≥ 10 g/dL.

Figure 2. Cumulative primary intervention volumes during 24 hr ICU resuscitation for CVP (not reassigned), PAC (initially assigned) and CVP – PAC (transition) protocol subgroups:

a. Crystalloid fluid infusion volumes for CVP protocol subgroup patients were less than required by PAC and CVP – PAC protocol subgroup patients ($p < 0.05$), possibly reflecting less severe shock, injury, and volume requirement to attain and maintain protocol hemodynamic performance goals.

b. PRBC transfusion volumes for CVP protocol subgroup patients were less than required by PAC protocol subgroup patients ($p < 0.05$), possibly reflecting less severe injury and ongoing blood loss during ICU resuscitation. PRBC transfusion volumes for CVP – PAC protocol subgroup patients were similar to CVP (not reassigned) and PAC (initially assigned), possibly reflecting use of both protocol processes during the 1st ICU day.

[a, b] indicate $p<0.05$

Figure 3. Protocol performance:

a. Central venous pressure (CVP) and pulmonary capillary wedge pressure (PCWP) for CVP (not reassigned), PAC (initially assigned) and CVP – PAC (transition) protocol subgroups during ICU resuscitation. CVP for the CVP (not reassigned) protocol subgroup patients was less than that for the CVP –PAC (transition) subgroup ($p < 0.05$) during the 1st 6 hr of ICU resuscitation, possibly reflecting less severe shock, injury, and volume requirement to attain and maintain the CVP protocol hemodynamic performance goal. PCWP for the PAC (initially assigned) protocol subgroup was less than that of the CVP – PAC (transition) protocol subgroup ($p < 0.05$) after transition from CVP to PAC directed protocol, possibly reflecting CVP protocol directed preload, and ongoing, persistent shock and hemodynamic instability of the CVP – PAC subgroup. Protocol directed goals are shown for reference: CVP ≥ 10 mmHg for the CVP protocol (attained ~8 hr after protocol start). The PAC

protocol hemodynamic performance goal was oxygen delivery index (DO_2I) ≥ 500 mL O_2/min-m^2, and could require PCWP ≥ 15 mmHg to achieve this goal with lactated Ringer's fluid infusion as the primary intervention.

b. Hemoglobin concentration ([Hb]) during ICU resuscitation for CVP, PAC and CVP – PAC protocol subgroups. CVP and PAC protocol goals were [Hb] ≥ 10 g/dL, with transfusion threshold of [Hb] < 9 g/dL. For CVP and PAC protocol subgroups, mean [Hb] ~ 11 g/dL exceeded CVP and PAC protocol goals throughout 24 hr ICU resuscitation. For the CVP – PAC protocol subgroup, mean [Hb] decreased from ~11.6 to ~9.1 g/dL in the initial 4 hours and then corrected to mean [Hb] > 10 with decision to change from CVP to PAC protocol, but [Hb] did not differ significantly from that of PAC protocol patients throughout ICU resuscitation.

[a, b, c] indicate $p<0.05$

Figure 4. Hemodynamic stability during ICU day 1:

a. MAP during ICU resuscitation for CVP, PAC and CVP – PAC protocol subgroups. MAP of PAC was less than that of CVP protocol subgroup patients, and MAP of CVP – PAC was less than that of PAC and CVP protocol subgroup patients ($p < 0.05$). For the CVP – PAC protocol subgroup, hemodynamic stability recovered to a course indistinguishable from the PAC protocol subgroup, possibly reflecting improved management using more direct hemodynamic (cardiac) monitoring provided by the PAC.

b. HR during ICU resuscitation for CVP, PAC and CVP – PAC protocol subgroups. HR for CVP was less than that for PAC and CVP – PAC protocol subgroup patients ($p < 0.05$).

[a, b, c] indicate $p<0.05$

Figure 5. Metabolic indicators of response to ongoing resuscitation.

a. Base deficit (BD) during ICU resuscitation for CVP, PAC and CVP – PAC protocol subgroups. BD of PAC exceeded that of CVP protocol subgroup patients at start and throughout ICU resuscitation ($p < 0.05$). For the CVP – PAC protocol subgroup, BD was similar to that of the PAC protocol subgroup.

b. Lactate concentration ([lactate]) during ICU resuscitation for CVP, PAC and CVP – PAC protocol subgroups. [lactate] for CVP protocol subgroup was less than that of PAC and CVP- PAC protocol subgroup patients at start and throughout ICU resuscitation ($p < 0.05$). [lactate] was similar for PAC and CVP – PAC protocol subgroup patients at start and throughout ICU resuscitation.

[a, b] indicate $p<0.05$

Figure 1

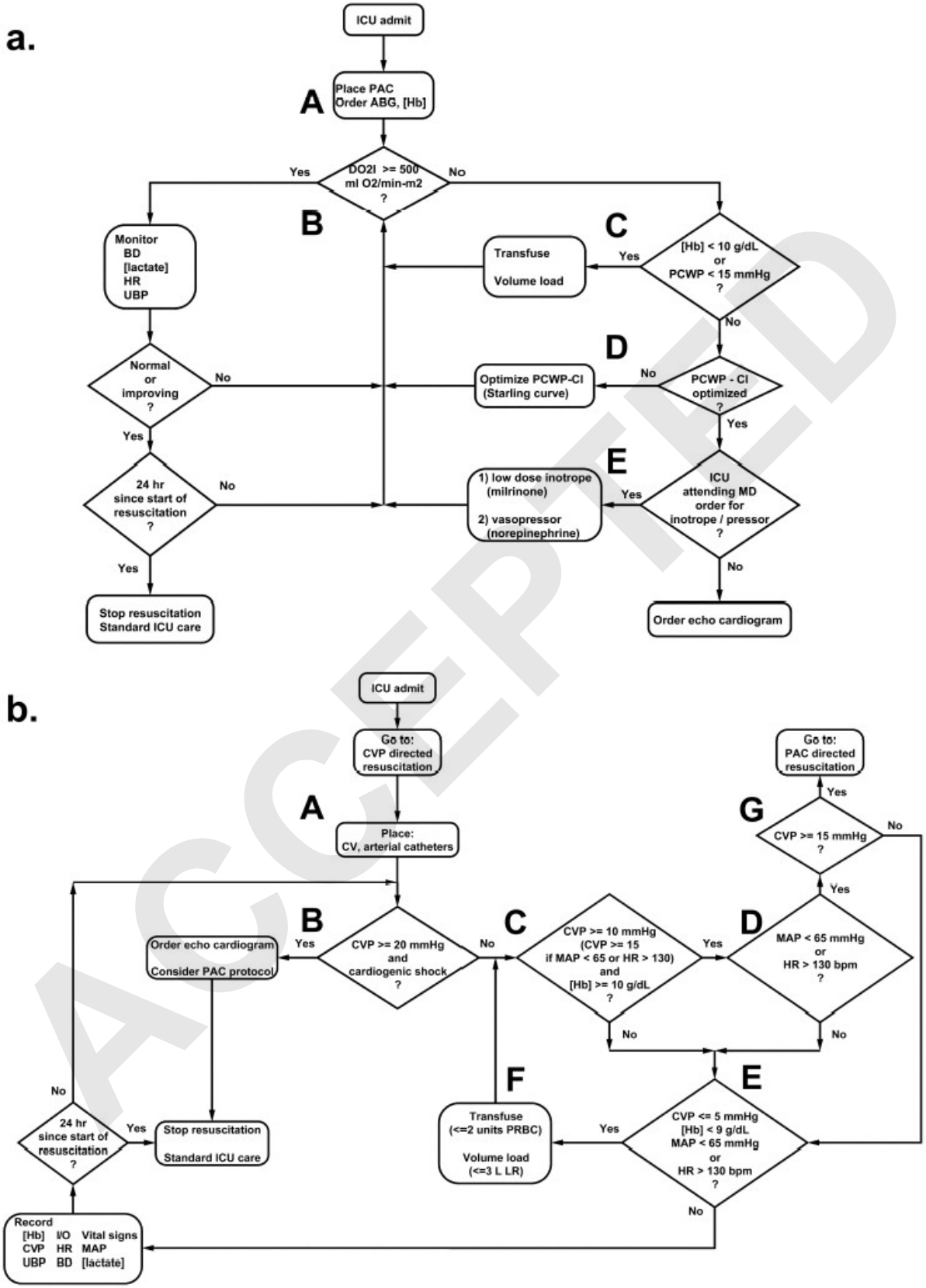

Figure 2

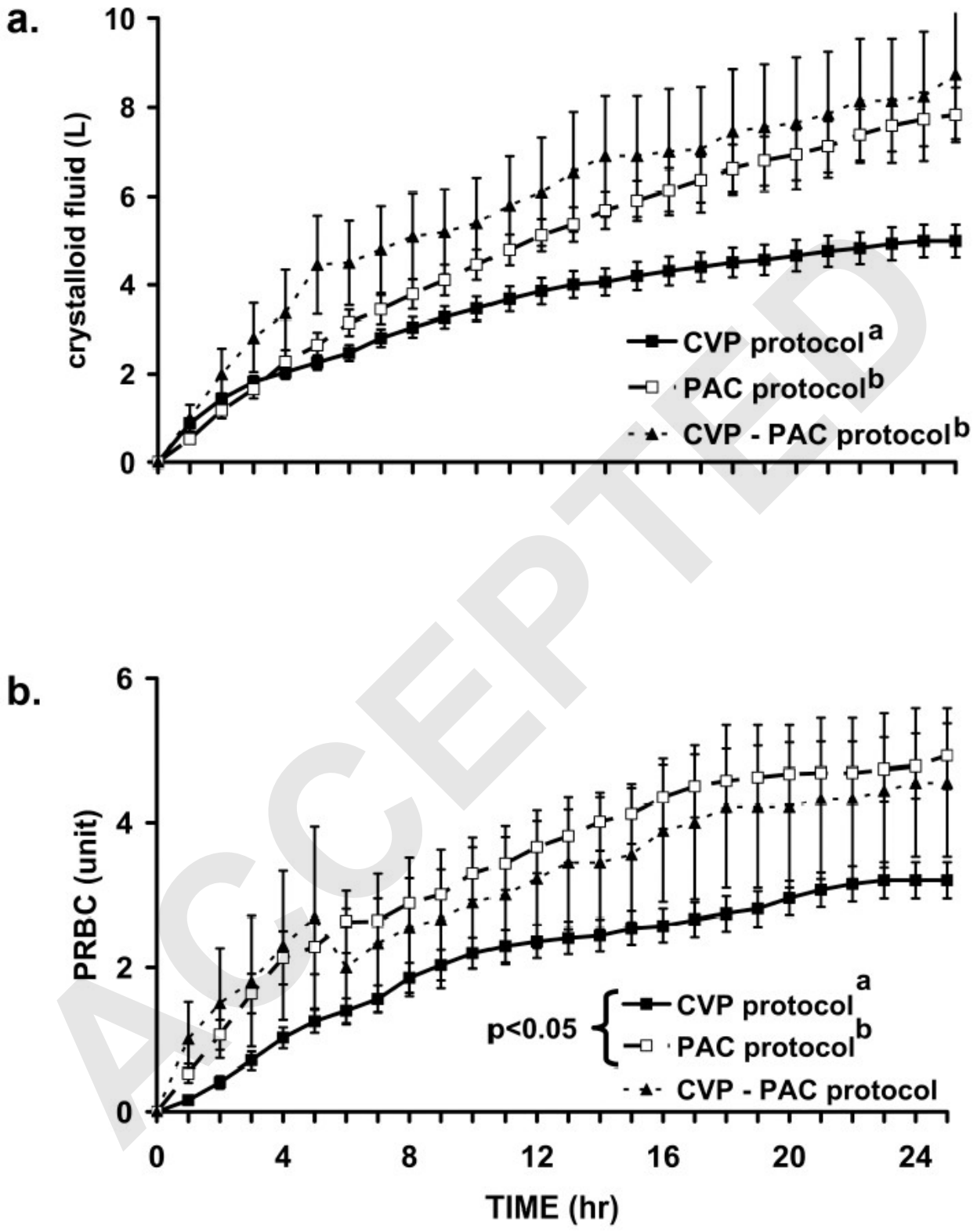

Figure 3

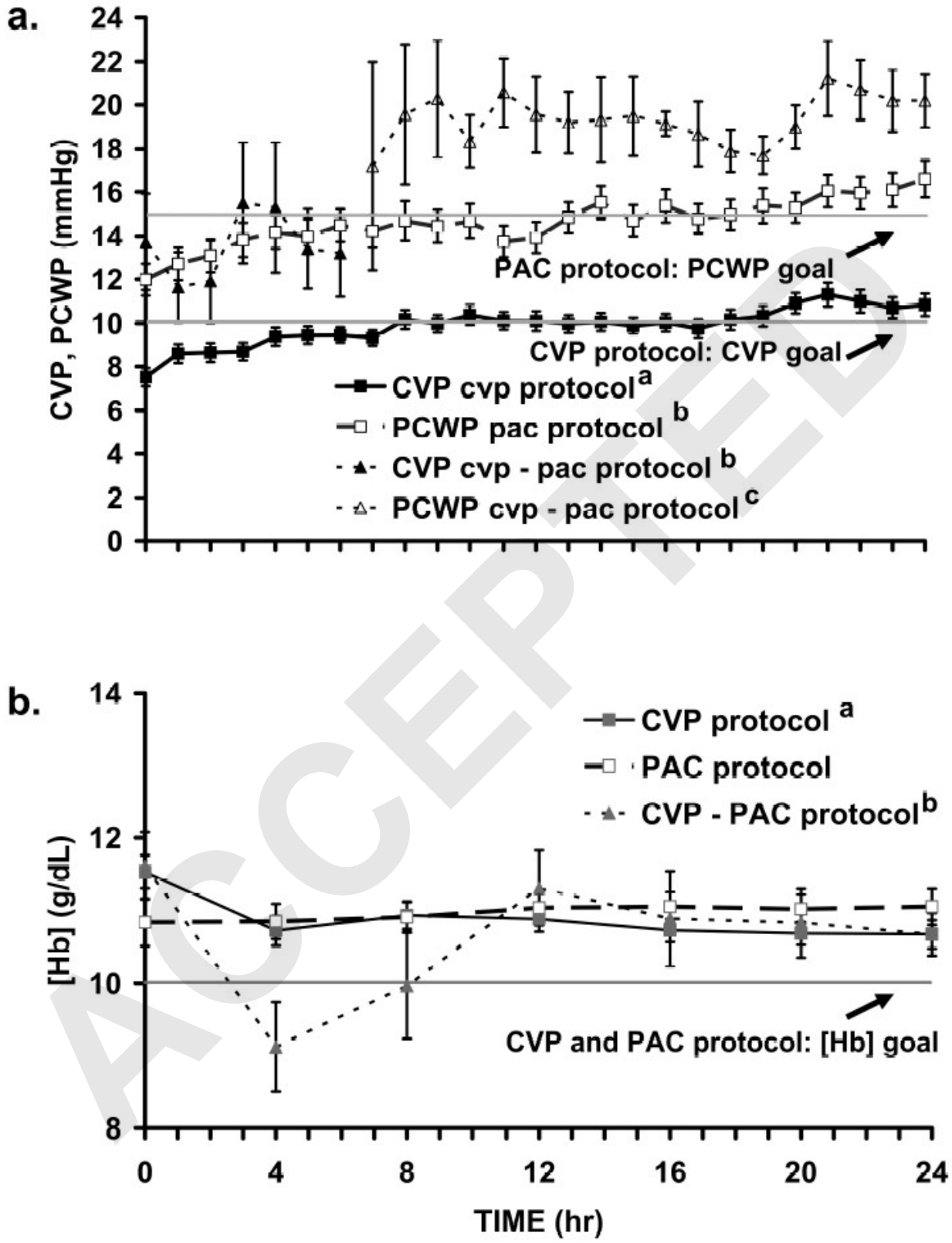

Figure 4

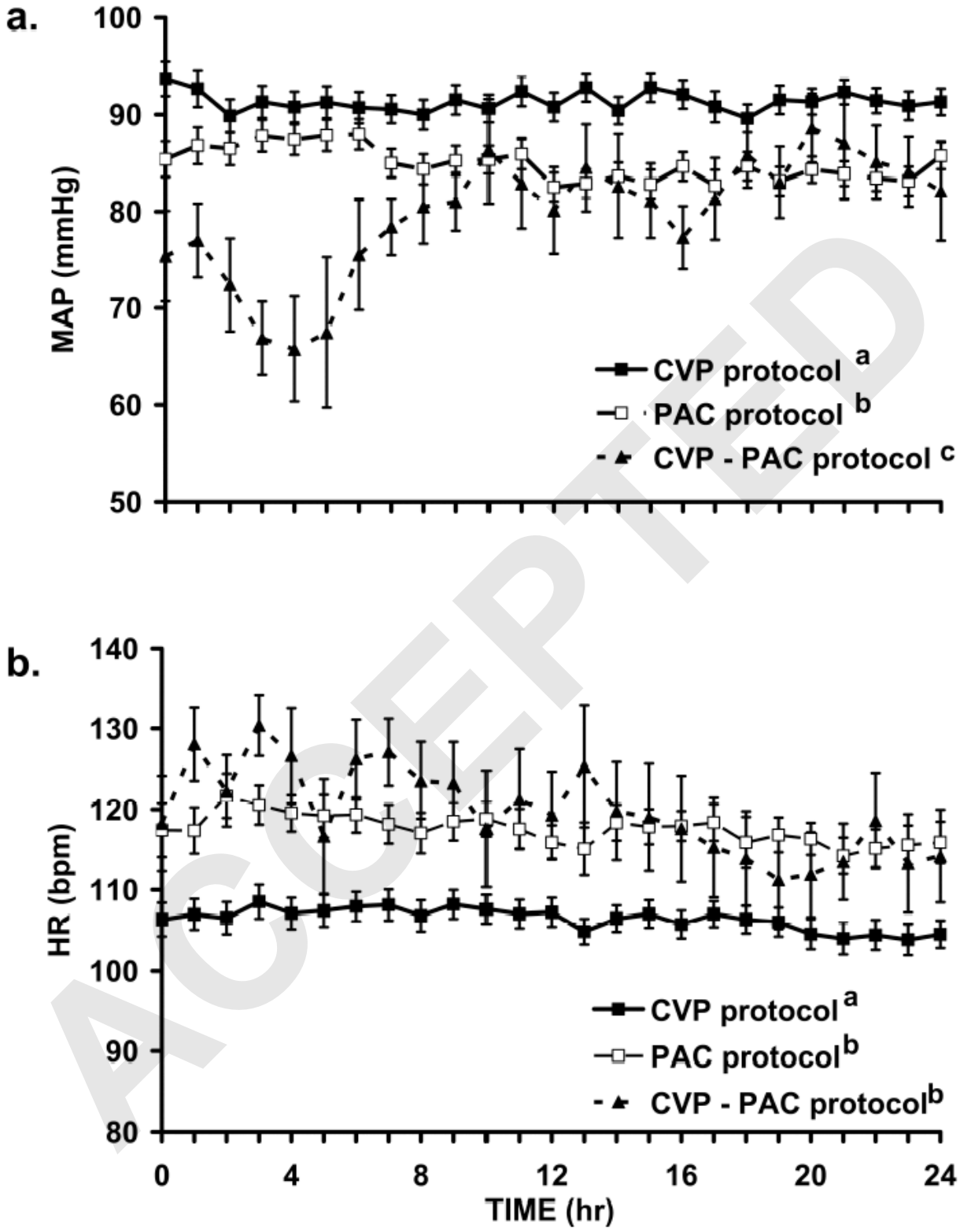

Figure 5