University of Michigan, Ann Arbor, MI
  Department of Surgery
  Section of Emergency Medicine
  (SAS, SCD, XW)

Address for correspondence and reprints:
  Susan A. Stern, MD
  Section of Emergency Medicine
  University of Michigan Medical Center
  TC-B1354-0303
  1500 East Medical Center Drive
  Ann Arbor, MI 48109-0303

■ SCIENTIFIC ADVANCES

Multiple Resuscitation Regimens in a Near-fatal Porcine Aortic Injury Hemorrhage Model

Susan A. Stern, MD, Steven C. Dronen, MD, Xu Wang, MD

■ ABSTRACT

Objective: To compare early and delayed blood administrations in animals subjected to near-fatal hemorrhage in the presence of a vascular injury and resuscitated to different mean arterial pressures (MAPs).

Methods: Fifty-four immature swine with 4-mm infrarenal aortic tears were bled to a pulse pressure of 5 torr and then resuscitated (estimated blood loss 40 to 45 mL/kg). Groups I, II, and III were resuscitated with shed blood at a rate of 2 mL/kg/min, followed by normal saline at a rate of 6 mL/kg/min. Groups IV, V, and VI received the same fluids in reverse order. The fluids were infused intermittently to maintain MAPs of 40, 60, and 80 torr. The animals were observed for 60 minutes or until death.

Results: The animals resuscitated to a MAP of 80 torr experienced significantly higher intraperitoneal hemorrhage volumes and mortality than did the animals intentionally maintained hypotensive, regardless of whether blood or normal saline was administered first. There was no significant difference in mortality or hemorrhage volumes between any of the groups intentionally maintained hypotensive. The animals maintained at a MAP of 60 torr were significantly less acidotic than were the animals resuscitated with the same fluid regimen but to a MAP of 40 torr. Early blood administration also minimized the acidosis associated with hypotensive resuscitation.

Conclusion: In this model of near-fatal hemorrhage with a vascular injury, maintenance of the hypotensive state produced comparable improvements in one-hour survival and reductions in hemorrhage volume regardless of whether blood or saline was administered first. Although hypotensive resuscitation resulted in improved outcome, it was associated with significant acidosis. This effect was minimized with moderate rather than severe underresuscitation and early blood administration.

Acad. Emerg. Med. 1995; 2:89–97.

The standard approach to the preoperative management of acute hemorrhagic hypotension is to restore normal or near-normal blood pressure (BP) with rapid infusion of isotonic crystalloid.[1] Recent studies from several laboratories have demonstrated that aggressive volume replacement and restoration of normotension may be harmful in the presence of a vascular injury.[2-7] In these studies, rapid volume expansion consistent with current Advanced Trauma Life Support guidelines[1] resulted in increased hemorrhage from the injury site and higher short-term mortality. A proposed mechanism for the poor outcome among the aggressively treated animals was a pressure-related failure of an already formed clot. Previous studies from our laboratory, using a near-fatal porcine aortic injury model, demonstrated improved one-hour survival and decreased hemorrhage volume for animals intentionally maintained hypotensive [mean arterial pressure (MAP) = 40 or 60 torr] as compared with those in which restoration of normotension was attempted.[7] Although hypotensive resuscitation resulted in improved outcome, it was at the expense of tissue perfusion, as evidenced by extreme decreases in serum bicarbonate and increases in serum lactate levels.

A more optimal resuscitation regimen would minimize hemorrhage volume while maximizing tissue oxygenation. In our prior studies, isotonic crystalloid was the initial and primary resuscitative agent.[6,7] Blood was administered only late in the resuscitation and in relatively small volumes. Initial resuscitation with blood rather than crystalloid may reduce the acidosis and improve tissue O_2 delivery in animals maintained hypotensive. The objective of the present study was therefore to compare early and delayed blood administrations in animals subjected to near-fatal hemorrhage in the presence of a vascular injury and resuscitated to MAPs of 40, 60, and 80 torr. We hypothesized that hypotensive resuscitation with early blood administration would result in the lowest hemorrhage volume and mortality while maintaining better tissue perfusion.

METHODS

Study Design

This was a randomized study of multiple resuscitation regimens in a near-fatal porcine aortic injury hemorrhage model. The study specifically compared early and delayed blood administrations in animals resuscitated to MAPs of 40, 60, and 80 torr.

Animals Subjects

The study used 54 immature Yorkshire swine, 3–4 months old, weighing 14.8–21.4 kg. The protocol was approved by the University of Cincinnati Institutional Animal Care and Use Committee and adhered to NIH guidelines for the use of laboratory animals.

Experimental Protocol

To successfully test our hypothesis required a reproducible near-fatal hemorrhage model that incorporated a vascular injury. Hemorrhage volumes and survival times are potentially quite variable with large vascular injuries. It is therefore difficult to consistently produce a severe life-threatening hemorrhage that is responsive to therapeutic intervention. We have solved this problem through the use of a hybrid "uncontrolled" hemorrhage model, a modification of Bickell et al.'s swine aortotomy model.[8] In our model, preresuscitative hemorrhage is accurately controlled from a femoral artery catheter. Once the animal reaches a predetermined physiologic endpoint, we inflict an aortic tear, allowing free intraperitoneal hemorrhage. This allows hemorrhage and resuscitation to occur simultaneously. This model is highly reproducible and has a one-hour mortality rate approaching 90% if the animal is not immediately resuscitated. The model is responsive to various therapeutic regimens, permitting evaluation of the effect of resuscitation on the vascular injury.[6,7]

The animals were fasted overnight with water ad libitum. Just prior to the study, the animals were lightly anesthetized with ketamine (300 mg IM) and placed supine on the operating table. A mixture of 2.0% halothane, 33% O_2, and 65% nitrous oxide (N_2O) was then administered via nose cone. When a surgical plane of anesthesia was reached, the animals were orotracheally intubated and the halothane concentration was reduced to 0.75%. All the animals maintained spontaneous respirations with this anesthetic mixture.

The abdomen, the anterior surface of the neck, and the femoral areas were shaved and prepped with povidone–iodine solution. The right and left femoral arteries were isolated via cutdown and cannulated with polyethylene catheters (1.67 mm ID). The left femoral catheter was connected to a Statham P23I transducer (Statham Instruments, Hato Rey, Puerto Rico) for continuous BP monitoring. The right femoral exsanguination catheter was connected to a Master-Flex #7550 Roller Pump Drive (Cole Parmer Instrument Company, Chicago, IL) regulated by an IBM PC. The femoral veins were isolated and cannulated via cutdown for drug and fluid administration and blood sampling. A 5-Fr flow-directed thermodilution Swan-Ganz catheter was inserted via the right external jugular vein and advanced into the pulmonary artery. This catheter was connected to a Statham P23I transducer and an American Edward cardiac output (CO) computer (American Edwards Laboratories, Irvine, CA) for central venous pressure

TABLE 1 Resuscitation Regimens

	Goal MAP (torr)	First Infusion	Second Infusion
Group I (n = 9)	40	Shed blood	Normal saline
Group II (n = 9)	60	Shed blood	Normal saline
Group III (n = 9)	80	Shed blood	Normal saline
Group IV (n = 9)	40	Normal saline	Shed blood
Group V (n = 9)	60	Normal saline	Shed blood
Group VI (n = 9)	80	Normal saline	Shed blood

(CVP), CO, and core body temperature measurements. To maintain patency, the catheters were flushed every 15 minutes with 1 mL of 0.3% heparin in normal saline (NS).

Splenectomy was performed to eliminate the effects of splenic sequestration and autotransfusion on hemo-dynamics.[9] The spleen was removed through a midline abdominal incision according to standard techniques, with double ligation of all vascular pedicles. The ret-roperitoneal fascia was incised and the anterior infra-renal aorta exposed. A 4.0 monofilament stainless-steel surgical wire was then placed through the anterior wall of the aorta into the aortic lumen, advanced, and exited at a point 4 mm distal. The wire ends were exteriorized and the abdominal incision was closed.

Following instrumentation, the halothane adminis-tration was discontinued. Sedation was maintained with 67% N_2O and lorazepam was administered in 1- to 2-mg boluses IV as needed. Thirty minutes after the halothane had been discontinued, baseline metabolic and hemodynamic measurements were obtained and hemorrhage was initiated from the right femoral artery catheter. To duplicate more closely the physiology and kinetics of hemorrhagic shock, the computer was pro-grammed to withdraw blood at a rate that decreased exponentially over time according to the following for-mula:

$$V = B_0 (1 - e^{-B_1 t})$$

where V = total blood loss at time t (mL/kg), B_0 = 64.40, B_1 = 0.04, and t = percentage of time until death. This formula was derived from a previous study conducted in our laboratory in which animals were bled spontaneously from a large vascular injury (unpublished data). This model mimics traumatic hemorrhage in that the initial bleed rate is rapid but decreases with the fall in BP. The computer was programmed to withdraw a maximum hemorrhage volume of 45 mL/kg over 30 minutes. Shed blood from the femoral artery catheter was placed in a blood collection bag containing 0.067 mL of citrate (CPD Solution, USP; Abbott Laborato-ries, Abbott Park, IL) per mL of blood for an estimated

hemorrhage volume of 40 mL/kg (swine body mass). Once the animal's MAP decreased to 30 torr the aor-totomy wire was pulled, producing a fixed vascular le-sion and free intraperitoneal bleeding. The catheter hemorrhage was discontinued and resuscitation was be-gun when the pulse pressure (systolic pressure minus diastolic pressure) decreased to 5 torr.

Fifty-four animals were alternately assigned to one of six resuscitation regimens (Table 1). Animals were resuscitated to a MAP of either 40, 60, or 80 torr. The animals in Groups I, II, and III were initially resusci-tated with shed blood infused at a rate of 2 mL/kg/min. The infusion was discontinued once the desired MAP was reached, and restarted if the MAP fell 5 torr below this point. After 30 minutes or a total shed blood in-fusion of 24 mL/kg, whichever came first, the resusci-tation fluid was changed to NS infused at a rate of 6 mL/kg/min, again as needed to maintain the desired MAP. The animals received a maximum volume of 90 mL/kg of NS. The animals in groups IV, V, and VI received the same resuscitation fluids but in the reverse order (Table 1).

The animals were observed for 60 minutes or until death, which was defined as a pulse pressure of 0. The animals that survived to 60 minutes were euthanized with 100 mg/kg of sodium pentobarbital IV. Following death, the peritoneal cavity was opened and the intra-peritoneal fluid and thrombus were collected and ho-mogenized for volume and hemoglobin measurements. All ligated vessels were inspected, and the aorta was resected for examination of the aortotomy site (Fig. 1).

Measurements

Beginning at baseline, heart rate, systolic pressure, diastolic pressure, MAP, and CVP were continuously recorded on a multichannel physiograph (Hewlett-Packard #7758, Waltham, MA). Respiratory rate and core body temperature were recorded at baseline and at 5-minute intervals thereafter. At baseline, at the ini-tiation of resuscitation (time 0), and at 15-minute in-tervals thereafter, arterial and venous blood samples were collected for blood gas analysis and hemoglobin
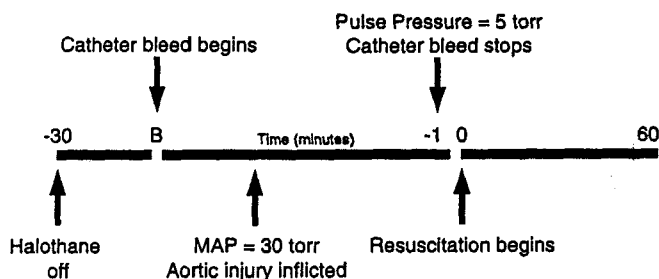
FIGURE 1. The experimental protocol. B = baseline; MAP = mean arterial pressure.

TABLE 2 Survival Time and Mortality

	Survival Time (min)	Mortality (%)
Group I	58 ± 7	11
Group II	57 ± 8	11
Group III	44 ± 12*	78*
Group IV	58 ± 6	11
Group V	59 ± 3	22
Group VI	44 ± 12†	78†

*p < 0.05, group III vs groups I, II, IV, and V.
†p < 0.05, group VI vs groups I, II, IV, and V.

TABLE 3 Infusion Volumes

	Normal Saline (mL/kg) mean (range)	Blood (mL/kg) mean (range)
Group I	6 (0–28)*	21 (11–24)
Group II	4 (0–34)*	23 (20–30)
Group III	90 (88–90)†	24 (24)
Group IV	48 (17–79)	13 (0–24)‡
Group V	51 (6–90)	10 (0–24)‡
Group VI	90 (90)†	22 (10–24)

*p < 0.05, groups I and II vs groups III, IV, V, and VI.
†p < 0.05, groups III and VI vs groups I, II, IV, and V.
‡p < 0.05, groups IV and V vs groups I, II, III, and VI.

(Hb) and hematocrit determinations. We used the thermodilution technique to measure COs at baseline and at 15-minute intervals throughout the resuscitation period. Arterial O_2 content and delivery were calculated using the following formulas:

$$CaO_2 = (1.39 \times Hb \times SaO_2) + (0.003 \times PaO_2)$$

$$DO_2 = (CO \times CaO_2 \times 10)/\text{body weight (kg)}$$

where CaO_2 = arterial O_2 content (mL/dL); Hb = hemoglobin (g/dL); SaO_2 = arterial O_2 saturation (%); PaO_2 = arterial partial pressure of O_2 (torr); DO_2 = O_2 delivery (mL/kg/min); and CO = cardiac output (L/min).

Data Analysis

Results are reported as the mean ± SD or the mean with accompanying range of values. The effects of early blood administration and BP on measured physiologic parameters, hemorrhage volumes, and survival times were analyzed using a two-way analysis of variance (ANOVA). Individual group differences were then assessed using one-way ANOVA with a post-hoc Tukey-Kramer analysis. Repeated measures were used when analyzing longitudinally measured parameters. The ef-

fects of early blood administration and BP on mortality were assessed using chi-square analysis. Mortality differences between individual groups were then assessed using Fisher's exact test. A p-value < 0.05 was considered significant throughout.

RESULTS

Mean prehemorrhage body masses were similar between groups. There was no clinically significant difference in baseline or preresuscitative physiologic parameters.

Mortality

Regardless of the initial resuscitative agent, attempts to restore normotension (groups III and VI) resulted in significantly higher mortality and lower survival times. There was no significant difference between any of the groups resuscitated to a MAP of 40 or 60 torr, regardless of the initial fluid administered (Table 2).

Infusion Volumes

Groups I, II, and III had similar shed blood requirements. Group III, however, required significantly more NS than did groups I and II. Group VI required significantly higher volumes of both NS and shed blood than did groups IV and V. Groups I and II received significantly higher volumes of shed blood but lower volumes of NS than did groups IV and V (Table 3).

Hemorrhage Volumes

Catheter hemorrhage volumes were similar except between groups II and V. Intraperitoneal and therefore total hemorrhage volumes were significantly higher in the animals in which normotension was the resuscitative goal (groups III and VI), regardless of the initial fluid administered. There was no significant difference in intraperitoneal or total hemorrhage volumes between any of the groups resuscitated to MAPs of 40 or 60 torr (Table 4). Upon necropsy, all aortotomy defects were 4 mm long and longitudinal, with organized clot surrounding the injury site.

Hemodynamic Responses

The animals in groups III and VI were unable to sustain a MAP of 80 torr even with aggressive fluid resuscitation. During the early part of the resuscitation, the pulse pressures of the animals for which normotension was the resuscitative goal (groups III and VI) were significantly higher than those of the animals intentionally maintained hypotensive (Fig. 2).

The cardiac indexes of the animals resuscitated to
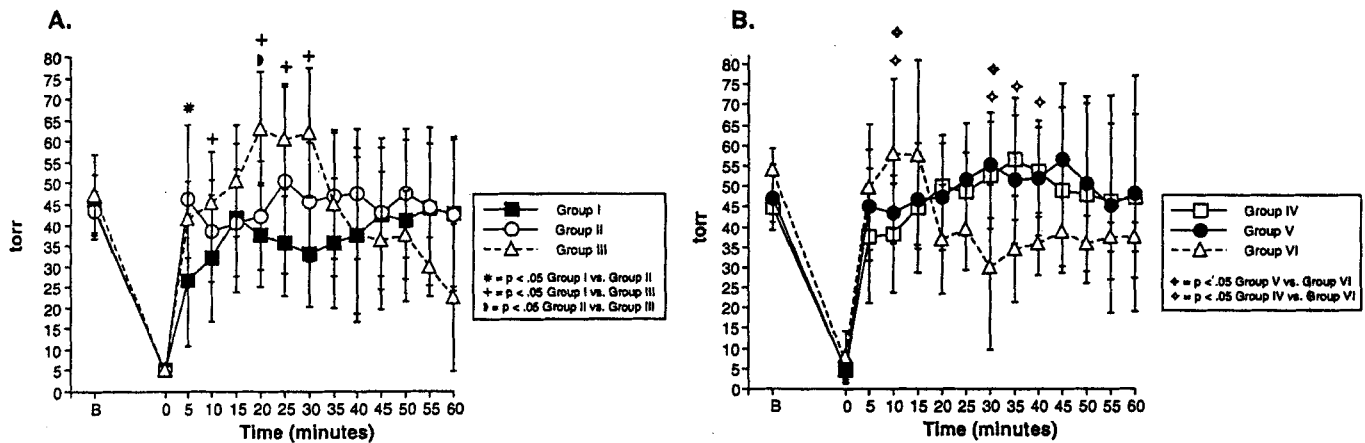
FIGURE 2. Pulse pressure for groups I–III (A) and groups IV–VI (B).

a MAP of 60 torr were significantly higher than those of the animals resuscitated to a MAP of 40 torr with the same fluid regimen (group I vs II and group IV vs V). The cardiac indexes of the animals resuscitated to the same MAP but with different fluid regimens were not different overall (group I vs IV and group II vs V) (Fig. 3).

Hemoglobin and Hematocrit

In all the groups, mean Hb and hematocrit measurements were significantly decreased from baseline at the start of resuscitation. Attempts to restore nor-

motension (groups III and VI) resulted in significantly lower Hb and hematocrit levels regardless of the initial resuscitative agent. Groups I and II maintained significantly higher Hb levels and hematocrits than did groups IV and V. The Hb level and hematocrit increased with resuscitation in groups I and II but decreased in groups IV and V (Table 5).

Oxygen Content

Like Hb and hematocrit, CaO_2 in all groups was significantly decreased from baseline at the start of resuscitation. Attempts to restore normotension resulted
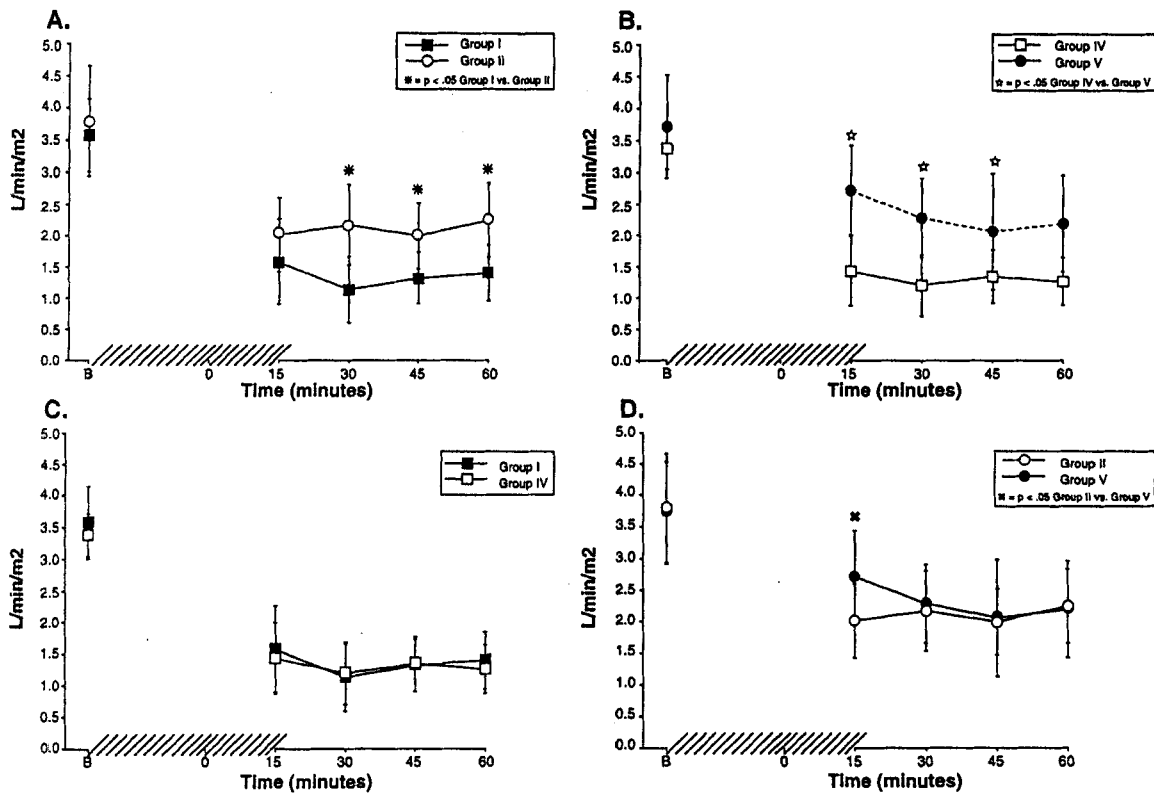
FIGURE 3. Cardiac indexes among the six groups.

TABLE 4 Hemorrhage Volumes

	Catheter Hemorrhage Volume (mL/kg) mean (range)	Intraperitoneal Hemorrhage Volume (mL/kg) mean (range)	Total Hemorrhage Volume (mL/kg) mean (range)
Group I	40 (34–48)	11 (2–20)	51 (42–65)
Group II	41 (34–49)*	11 (3–29)	52 (39–74)
Group III	40 (36–42)	62 (51–68)†	95 (40–108)†
Group IV	37 (34–41)	13 (5–49)	50 (41–87)
Group V	36 (32–40)	20 (4–70)	56 (36–102)
Group Vi	37 (32–45)	46 (28–65)‡	83 (69–99)‡

*p < 0.05, group II vs group V.
†p < 0.05, group III vs groups I, II, IV, and V.
‡p < 0.05, group VI vs groups I, II, IV, and V.

in significantly lower O_2 contents than did maintenance of a hypotensive state, regardless of the initial resuscitative agent. Groups I and II maintained significantly higher CaO_2s than did groups IV and V (Fig. 4).

Oxygen Delivery

In all groups, DO_2 decreased significantly from baseline with hemorrhage. The DO_2s were significantly higher in the animals resuscitated to a MAP of 60 torr as compared with 40 torr, regardless of the initial resuscitative agent (group I vs II and group IV vs V).
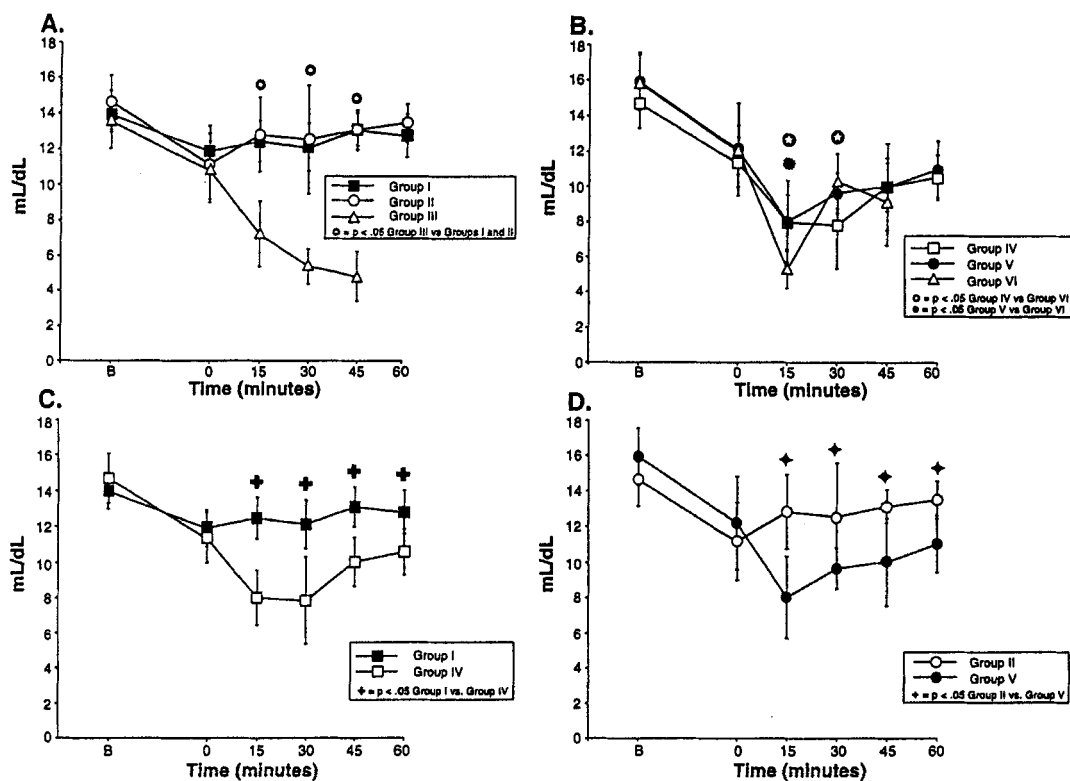
Overall, The DO_2s did not differ significantly between those groups resuscitated to the same MAP but with different fluid regimens (group I vs IV and group II vs V). The exception to this occurred at 15 minutes, when the DO_2 was significantly higher in group I than it was in group IV (Fig. 5).
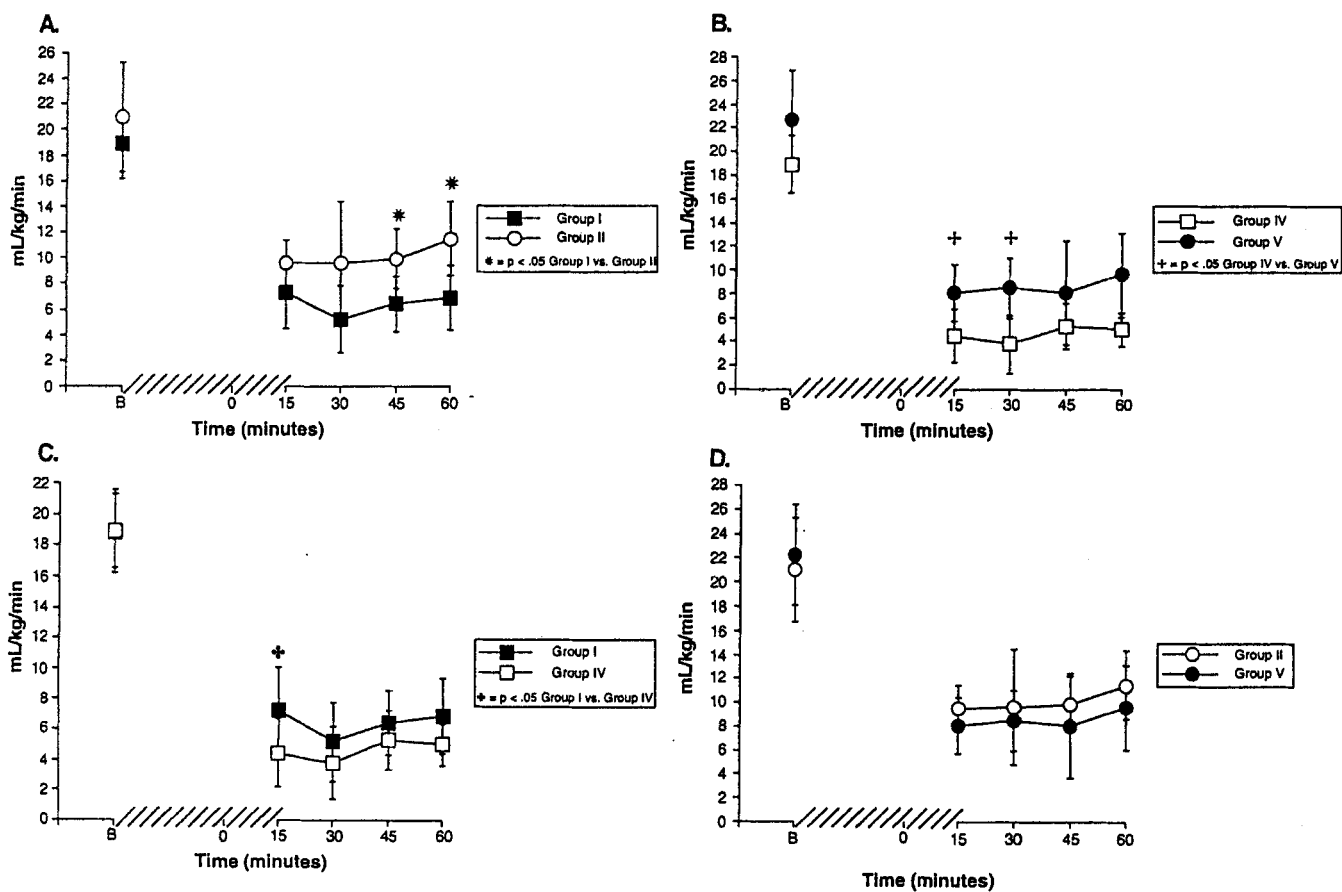
Metabolic Response

Resuscitation to a MAP of 60 torr resulted in significantly less acidosis than did resuscitation to a MAP of 40 torr (group I vs II and group IV vs V). Also, the animals maintained hypotensive and initially given shed blood were less acidotic than those animals maintained at the same level of hypotension but administered NS first (group I vs IV and group II vs V) (Table 6).

DISCUSSION

Our data show that attempts to restore normotension during acute hemorrhage in the presence of a vascular injury result in significant increases in hemorrhage volume and mortality. The data further show that this is true regardless of whether blood or crystalloid is administered first, but that early blood administration reduces the acidosis associated with maintenance of the hypotensive state. These results directly contradict the current dogma of rapid volume expansion for the preoperative management of acute hemorrhage. The re-

TABLE 5 Hematocrit (%)

	Baseline	0 min	15 min	30 min	45 min	60 min
Group I	30 ± 3	24 ± 2	27 ± 3*	27 ± 3*	28 ± 3*	26 ± 2*
Group II	32 ± 3	22 ± 4	29 ± 3†	27 ± 3†	27 ± 3†	29 ± 3†
Group III	31 ± 2	25 ± 3	17 ± 2‡	12 ± 2‡	11 ± 3‡	—
Group IV	32 ± 2	23 ± 2	14 ± 4	14 ± 6	21 ± 3	22 ± 3
Group V	32 ± 2	23 ± 5	15 ± 5	18 ± 3	20 ± 4	22 ± 3
Group VI	33 ± 3	23 ± 3	9 ± 2§	22 ± 2	—	—

*p < 0.05, group I vs groups IV and V.
†p < 0.05, group II vs groups IV and V.
‡p < 0.05, group III vs groups I and II.
§p < 0.05, group VI vs groups I, II, III, IV, and V.

TABLE 6 Serum Bicarbonate (mmol/L)

	Baseline	0 min	15 min	30 min	45 min	60 min
Group I	25 ± 3*	30 ± 10	18 ± 4*	18 ± 7*	16 ± 6*†	16 ± 7*
Group II	25 ± 3‡	27 ± 9	20 ± 4	20 ± 5	21 ± 3‡	22 ± 3‡
Group III	29 ± 2	24 ± 11	17 ± 3	17 ± 4	14 ± 3	—
Group IV	29 ± 4	22 ± 4	13 ± 5§	10 ± 4§	9 ± 4§	8 ± 4§
Group V	32 ± 4	24 ± 5	20 ± 2	18 ± 4	16 ± 5	16 ± 4
Group VI	30 ± 3	21 ± 5	13 ± 3	11 ± 4	—	—

*p < 0.05, group I vs group IV.
†p < 0.05, group I vs group II.
‡p < 0.05, group II vs group V.
§p < 0.05, group IV vs group V.

FIGURE 4. Arterial oxygen content among the six groups.

FIGURE 5. Oxygen delivery among the six groups.

sults are, however, consistent with recent animal studies demonstrating poor outcome with aggressive volume replacement in the presence of a vascular injury.[2-7]

Several possible mechanisms may be responsible for the poor outcome observed in the aggressively resuscitated animals. These have been discussed in detail in a previous report[7] but may include the following: 1) The early rapid increases in pulse pressure experienced by animals for which normotension was the resuscitative goal may have disrupted what was likely to have been an initially soft and unstable thrombus, resulting in increased hemorrhage from the injury site. 2) The severe hemodilution and correspondingly low viscosity experienced by the aggressively resuscitated animals (groups III and VI) may have resulted in an increase in blood flow through the aortic tear.[10-13] 3) Finally, the severe hemodilution experienced by the animals in groups III and VI would result in further compromise of an already tenuous O_2-carrying capacity.

Although the data show that hypotensive resuscitation minimizes one hour-mortality, it is at the expense of tissue oxygenation; serum bicarbonate levels and DO_2s remained significantly reduced from baseline throughout the resuscitation in all groups. The data suggest there are two methods of minimizing these potentially deleterious effects. First, moderate underresuscitation (target MAP = 60 torr) resulted in significantly higher serum bicarbonate levels and DO_2s than did severe underresuscitation (target MAP = 40 torr), regardless of the initial resuscitative agent. Importantly, moderate underresuscitation provided these benefits without causing significant increases in either hemorrhage volume or mortality.

The second method of maximizing tissue perfusion is via early blood administration. The administration of crystalloid during severe hemorrhage further dilutes an animal's already compromised O_2-carrying capacity. Gump et al. demonstrated the effect of this hemodilution on DO_2 in dogs.[14] In their study, stepwise hemodilution resulted in progressive decreases in DO_2 in spite of accompanying increases in CO. In the present study, initial resuscitation with NS (groups IV and V) resulted in further significant decreases in CaO_2. In contrast, the CaO_2 did not change when the animals were initially resuscitated with whole blood (groups I and II). Groups I and II maintained significantly higher CaO_2s than did groups IV and V throughout the resuscitation. The higher CaO_2 translated into improved DO_2 only when comparing groups I and IV 15 minutes into the resuscitation.

The inability to persistently show statistically significant differences in mean DO_2 between the two resuscitation regimens likely reflects the small group sizes and large SDs. While mean DO_2s did not differ, the differences in DO_2 nadirs did approach significance.

Minimum DO_2 nadirs were 4.6 ± 2.2 mL/kg/min, 9.0 ± 2.2 mL/kg/min, 3.3 ± 1.5 mL/kg/min, and 6.7 ± 3.0 mL/kg/min for groups I, II, IV, and V, respectively. The 95% CIs for the differences in DO_2 nadirs between groups I and IV and groups II and V were −0.6 to 3.3 and −0.6 to 4.9, respectively. These CIs evidence an obvious trend toward improved DO_2 in the animals that received blood first. Although this difference is not statistically significant, it may be clinically significant. Because the animals were observed only for 60 minutes, the long-term effect of the extremely low DO_2 and the potential benefits of the trend toward improved DO_2 in the animals administered blood first cannot be assessed. It is reasonable to assume, however, that improved DO_2 may minimize vital organ damage associated with a prolonged low flow state.

The data highlight a second advantage of blood over crystalloid as a resuscitative agent, i.e., its superior buffering capacity. Whole blood contains two readily available sources of acid buffer: proteins and bicarbonate. Crystalloid solutions, however, provide only indirect bicarbonate sources such as lactate or acetate. These substrates are metabolized to bicarbonate in the liver, provided adequate tissue oxygenation occurs, and then only after one to two hours. Traverso et al. compared the buffering capacities of various resuscitation solutions in vitro.[15] They noted human plasma to have 25 to 50 times the buffering capacity of crystalloid solutions and five times the buffering capacity of human serum albumin. In separate in-vitro studies of controlled near-fatal hemorrhage, Dronen et al.[16] and Traverso et al.[17] demonstrated significantly less acidosis with whole blood resuscitation as compared with crystalloid resuscitation. The current data are consistent with the results of these studies. The animals maintained hypotensive and resuscitated initially with shed blood had significantly higher serum bicarbonate levels than did the animals resuscitated to the same level of hypotension but primarily with crystalloid (group I vs IV and group II vs V).

In recapitulation, maintenance of the hypotensive state produces comparable reductions in hemorrhage from the site of a vascular injury and subsequent one-hour mortality, regardless of whether blood or crystalloid is used as the initial resuscitative agent. The data also show that moderate rather than severe underresuscitation better preserves tissue perfusion without significant increases in hemorrhage volume or one-hour mortality. Although early blood administration minimized acidosis and hemodilution, DO_2 was only minimally improved.

∎ CONCLUSION

The ideal resuscitation regimen for the preoperative management of hemorrhagic hypotension remains un-

defined. It is clear, however, that in this model of near-fatal acute hemorrhage, the current recommendation to attempt restoration of normotension with rapid volume expansion is not ideal. The therapeutic goal should be maintenance of adequate organ and tissue perfusion. In severe hemorrhage this requires volume expansion, but this must be titrated carefully to avoid overresuscitation, causing further hemorrhage from the injured vessel. In addition, early blood administration minimizes the acidosis associated with hypotensive resuscitation and avoids the hemodilution of crystalloid administration.

▌ REFERENCES

1. American College of Surgeons, Committee on Trauma. Advanced Trauma Life Support. Chicago: American College of Surgeons, 1988, pp 59–73.
2. Gross D, Landau EH, Assalia A, et al. Is hypertonic saline resuscitation safe in "uncontrolled" hemorrhagic shock? J Trauma. 1988; 28:751–6.
3. Gross D, Landau EH, Klin B, et al. Quantitative measurement of bleeding following hypertonic saline therapy in "uncontrolled" hemorrhagic shock. J Trauma. 1989; 29:79–83.
4. Gross D, Landau EH, Klin B, et al. Treatment of uncontrolled hemorrhagic shock with hypertonic saline solution. Surg Gynecol Obstet. 1990; 170:106–22.
5. Bickell WH, Bruttig SP, Wade CE, et al. The detrimental effects of IV crystalloid after aortotomy in the swine [abstract]. Ann Emerg Med. 1989; 18:476.
6. Kowalenko T, Stern SA, Dronen SC, et al. Improved outcome with hypotensive resuscitation of uncontrolled hemorrhagic shock in a swine model. J Trauma. 1992; 33:349–53.
7. Stern SA, Dronen SC, Birrer P, et al. The effect of blood pressure on hemorrhage volume and survival in a near-fatal hemorrhage model incorporating a vascular injury. Ann Emerg Med. 1993; 22:155–63.
8. Bickell WH, Bruttig SP, Wade CE. Hemodynamic response to abdominal aortotomy in the anesthetized swine. Circ Shock. 1989; 28:321–32.
9. Hannon JP, Bossone CA, Rodkey WG. Splenic red cell sequestration and blood volume measurements in conscious pigs. Am J Physiol. 1985; 248(Regul Integrative Comp Phys) R293–R301.
10. Repogle RL, Jundler H, Gross RE. Studies on the hemodynamic importance of blood viscosity. J Thorac Cardiovasc Surg. 1965; 50:658–68.
11. Hopkins RW, Fratianne RB, Rao KV, et al. Effects of hematocrit and viscosity on continuing hemorrhage. J Trauma. 1974; 14:482–93.
12. Wangensteen SL, Eddy DM, Ludewig RM. The hydrodynamics of arterial hemorrhage. Surgery. 1968; 64:912–21.
13. Guyton AC. Textbook of Medical Physiology, ed 7. Philadelphia: W. B. Saunders, 1986, p 32.
14. Gump FE, Butler H, Kinney JM. Oxygen transport and consumption during acute hemodilution. Ann Surg. 1968; 168:54–60.
15. Traverso LW, Medina F, Bolin RB. The buffering capacity of crystalloid and colloid resuscitation solutions. Resuscitation. 1985; 12:265–70.
16. Dronen SC, Stern S, Baldursson J, et al. Improved outcome with early blood administration in a near-fatal model of porcine hemorrhagic shock. Am J Emerg Med. 1992; 10:533–7.
17. Traverso LW, Hollenbach SJ, Bolin RB, et al. Fluid resuscitation after an otherwise fatal hemorrhage II. Colloid solutions. J Trauma. 1986; 26:176–82.