Supranormal Trauma Resuscitation Causes More Cases of Abdominal Compartment Syndrome

Zsolt Balogh, MD; Bruce A. McKinley, PhD; Christine S. Cocanour, MD; Rosemary A. Kozar, MD, PhD; Alicia Valdivia, RN; R. Matthew Sailors, PhD; Frederick A. Moore, MD

Hypothesis: Normal resuscitation (oxygen delivery index [DO2I] ≥500 mL/min per square meter), compared with supranormal trauma resuscitation (DO2I ≥600 mL/min per square meter), requires less crystalloid volume, thus decreasing the incidence of intra-abdominal hypertension (IAH) and abdominal compartment syndrome (ACS).

Design: Retrospective analysis of a prospective database.

Setting: Twenty-bed intensive care unit (ICU) in a regional level I trauma center.

Patients: Patients with major trauma (injury severity score ≥15, initial base deficit ≥6 mEq/L, or need for ≥6 units of packed red blood cells in the first 12 hours) or age 65 years or older with any 2 of the previous criteria.

Interventions: Shock/trauma resuscitation protocol: pulmonary artery catheter, gastric tonometry, urinary bladder pressure measurements, lactated Ringer infusion, packed red blood cell transfusion, and moderate inotrope support, as needed, in that sequence, to attain and maintain a DO2I greater than or equal to 600 mL/min per square meter (16 months, ending January 1, 2001, n=85) or a DO2I greater than or equal to 500 mL/min per square meter (16 months, starting January 1, 2001, n=71) for the first 24 hours in the ICU.

Main Outcome Measures: Lactated Ringer infusion volume (liters) at ICU admission, gastric partial carbon dioxide minus end-tidal carbon dioxide (GAP CO2), IAH (urinary bladder pressure measurements ≥20 mm Hg), ACS (urinary bladder pressure measurements ≥25 mm Hg with organ dysfunction), multiple organ failure, and mortality.

Results: Demographics, injury severity, and shock severity parameters were similar in both groups. The supranormal resuscitation group required more lactated Ringer infusion volume in the first 24 hours in the ICU (mean ± SD, 13 ± 2 vs 7 ± 1 L; P<.05) and had higher GAP CO2 (16 ± 2 vs 7 ± 1 mm Hg; P<.05). In the supranormal group, IAH (42% vs 20%; P<.05) and ACS (16% vs 8%; P<.05) were more frequent. The conventional trauma outcomes, such as multiple organ failure (22% vs 9%; P<.05) and mortality (27% vs 11%; P<.05) were less favorable in the supranormal resuscitation group.

Conclusion: Supranormal resuscitation, compared with normal resuscitation, was associated with more lactated Ringer infusion, decreased intestinal perfusion (higher GAP CO2), and an increased incidence of IAH, ACS, multiple organ failure, and death.

Arch Surg. 2003;138:637-643

POSTINJURY MULTIPLE organ failure (MOF) continues to be the major cause of prolonged intensive care unit (ICU) stay and mortality among trauma patients who survive the first 48 hours postinjury. To prevent MOF, the population at risk was determined, and a prediction model was developed during the early 1990s. The predictive model helps investigators to concentrate their preventive and therapeutic efforts on the population at highest risk for MOF. The independent predictors for MOF are age, injury severity measured by the injury severity score, and the severity of shock. Since age and injury severity score are not factors that we can control, resuscitation of hemorrhagic shock has become the focus in the prevention of MOF in many trauma centers. Shoemaker et al proposed that a supranormal oxygen delivery index (DO2I) (>600 mL/min per square meter) should be the optimal resuscitation goal, since they observed that DO2I was increased to supranormal levels in survivors compared with nonsurvivors, whose DO2I remained less than 600 mL/min per square meter. The concept that early supranormal DO2I values improved the outcome was reported in a series of publications. Later, several prospective randomized trials offered conflicting results. Shoemaker et
al recently showed, in a prospective randomized trial, that supranormal resuscitation does not have additional benefits on the outcome of critically injured patients.

We developed a computerized traumatic shock resuscitation protocol that is presumptively applied to trauma patients who are at high risk for MOF. This standardized resuscitation process is a standard of care at our ICU and provides a unique opportunity for prospective resuscitation data collection. From the initiation of the resuscitation protocol in 1997, we used the supranormal DO2I goal to attain and maintain during the first 24 hours after ICU admission. However, the ongoing concern regarding excessive volume loading prompted us to abandon the supranormal goal and, in January 2001, implement the DO2I resuscitation goal (>500 mL/min per square meter). Our recent study, comparing 18 patients who received supranormal resuscitation with 18 age-matched patients who received normal resuscitation, showed no difference in responses, but the supranormal group required more crystalloid loading. Clinical reports during the last 2 years have suggested the possible relationship between crystalloid loading and the development of intra-abdominal hypertension (IAH) and abdominal compartment syndrome (ACS). We developed a computerized traumatic shock resuscitation protocol that is presumptively applied to trauma patients who are at high risk for MOF. This standard-based process that emphasizes hemoglobin and volume loading to attain and maintain an oxygen delivery goal for the first 24 hours of ICU admission. Described previously, a hierarchical sequence of therapy interventions and thresholds for intervention is uniformly applied to all patients. Resuscitation is data driven to tailor the standardized process to the needs and responses of the individual patients. To achieve a DO2I greater than or equal to 600 mL/min per square meter (before January 2001) or a DO2I greater than or equal to 500 mL/min per square meter (from January 2001) for 24 hours, the protocol comprises a hierarchy of sequentially applied therapies (with intervention thresholds): (1) packed red blood cell transfusion (hemoglobin >10 g/dL [<12 g/dL if age ≥65 years]); (2) lactated Ringer solution (pulmonary capillary wedge pressure [PCWP] <15 mm Hg [<12 mm Hg if age ≥65 years]); (3) Starling curve to optimize the relationship between cardiac index and PCWP (hemoglobin ≥10 g/dL, PCWP ≥15 mm Hg, and DO2I >600 mL/min per square meter or DO2I ≥500 mL/min per square meter); (4) inotrope (cardiac index–PCWP optimized and DO2I >600 mL/min per square meter or DO2I ≥500 mL/min per square meter); and (5) vasopressor (mean arterial pressure <65 mm Hg).

As a part of the resuscitation protocol, intra-abdominal pressure was determined indirectly by measuring urinary bladder pressure (UBP) every 4 hours (or more frequently if it was ordered). Intra-abdominal hypertension was defined as a UBP greater than 20 mm Hg. Abdominal compartment syndrome was defined as a UBP greater than 25 mm Hg with acute organ (cardiac, pulmonary, or renal) dysfunction, reversible on abdominal decompression. A pulmonary artery catheter with continuous cardiac output and mixed venous hemoglobin oxygen saturation monitoring and a gastric tonometer-sump catheter with gastric mucosal interstitial partial pressure of carbon dioxide monitoring were placed. Current, essential measurements (hemoglobin concentration, cardiac index, arterial oxygen saturation, and PCWP) are used in decision making for therapy intervention in real time. The hierarchy sequence is based on these measurements and a comparison with established intervention thresholds.

## DATA ANALYSIS

Data were obtained prospectively during the protocol resuscitation process. A computer with touch screen and keyboard interfaces was used at bedside to enter necessary data, compare data with threshold rules, execute the logical process, and present instructions for intervention and/or monitoring. With the computer, both diagnostic data and interventions were recorded in real time for review. Retrospectively, the resuscitation response, interventions, and outcomes of supranormal and normal resuscitation patients were compared. The hemodynamic variables, cardiac index, PCWP, gastric regional mucosal carbon dioxide minus end tidal carbon dioxide (GAPCO2), UBP, and blood and fluid volumes during the time course of the resuscitation process were compared. Cohort demographics, the incidence of IAH and ACS, MOF, and survival outcomes were also compared.
Our shock resuscitation results support that supranormal trauma resuscitation is not superior to normal traumatic shock resuscitation. The supranormal and normal resuscitation cohorts had the same resuscitation response to our standardized shock resuscitation protocol. From the 2 demographically similar cohorts with identical shock and injury severity, the supranormal resuscitation patients required more LR loading to achieve the goal of a DO$_2$I greater than 600 mL/min per square meter. The normal resuscitation cohort (DO$_2$I goal >500 mL/min per square meter), with less crystalloid requirement, had better intestinal perfusion, lower UBP, and better outcome than those of the supranormal cohort.

Our observation is consistent with recent clinical reports that have suggested that supranormal resuscitation does not have an additional benefit over normal resuscitation. Furthermore, our study advocates that supranormal resuscitation can be harmful in a population of severely injured patients with predominantly blunt injuries.

In their recent prospective randomized study of 35 control and 40 supranormal resuscitation patients, Velmahos et al$^{12}$ concluded that early optimization does not improve the outcome in severely injured patients. Their study population had the same mean age (33 years) but their Injury Severity Score was lower (21 points) than in our present study population. Seventy-three percent of their population sustained penetrating trauma, while in our population, more than 80% of the patients had blunt trauma. The difference in injury mechanism can explain why Velmahos et al did not find any difference in outcome between supranormal and normal patients and why we found that supranormal resuscitation resulted in worse outcome. Velmahos et al also concluded that penetrating trauma is a predictor of optimal resuscitation response because it is associated with specific injuries that can be addressed surgically, unlike blunt trauma, which is usually caused by diffuse impact with multisystem effects that cannot always be controlled surgically.

A meta-analysis of 21 randomized controlled trials on hemodynamic optimization revealed a statistically significant reduction in mortality if patients with acute severe illness or injury were treated early to achieve optimal (supranormal) goals before the development of organ failure.$^{20}$ The hemodynamic optimization after the development of organ failure did not improve the outcome compared with control groups.

While the concept that maximizing oxygen delivery to eliminate flow-dependent oxygen consumption decreases MOF and the optimal DO$_2$I value remains controversial, we believe that a shock resuscitation protocol facilitates appropriate prioritization of resuscitation in the initial evaluation and management of major trauma. Moreover, a protocol facilitates early recognition of complications that would not be evident with standard monitoring. Examples include myocardial dysfunction, ongoing hemorrhage, and the development of ACS. The end point in resuscitation is difficult to define. Our approach is to aim for a DO$_2$I greater than 500 mL/min per square meter during the first 24 hours of resuscitation and to continue resuscitation beyond that time only if evidence of persistent perfusion deficits exists. Efforts to maintain a DO$_2$I greater than 500 mL/min per square meter beyond 24 hours is rarely beneficial, and to persist may be harmful.

### Table 1. Demographics, Injury, and Shock Severity of Supranormal and Normal Resuscitation Cohorts

<table>
<thead>
<tr>
<th></th>
<th>Supranormal Resuscitation</th>
<th>Normal Resuscitation</th>
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</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>37 ± 3</td>
<td>33 ± 2</td>
</tr>
<tr>
<td>Sex, % male</td>
<td>76</td>
<td>74</td>
</tr>
<tr>
<td>Injury mechanism, % blunt</td>
<td>84</td>
<td>90</td>
</tr>
<tr>
<td>ISS</td>
<td>28 ± 3</td>
<td>27 ± 2</td>
</tr>
<tr>
<td>Initial base deficit, mEq/L</td>
<td>9 ± 1</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>Serum lactate, 12-24 h, mmol/L</td>
<td>4.2 ± 1</td>
<td>3.9 ± 1</td>
</tr>
<tr>
<td>Pre-ICU PRBC transfusions, U</td>
<td>5 ± 1</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>Pre-ICU crystalloid infusions, L</td>
<td>6 ± 1</td>
<td>5 ± 1</td>
</tr>
</tbody>
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Abbreviations: ICU, intensive care unit; ISS, Injury Severity Score; PRBC, packed red blood cell.

*Data are given as mean ± SD unless otherwise indicated.

During the 32-month study period, 156 patients were resuscitated in the shock trauma ICU using our standardized shock resuscitation protocol. Eighty-five of these patients received supranormal DO$_2$I resuscitation and 71 received normal DO$_2$I resuscitation. Demographic, injury, and shock severity data are presented in Table 1. Supranormal and normal cohorts were not different in age, sex, injury mechanism, injury severity score, and initial severity of shock. In response to the initial shock, both cohorts were given the same amount of blood and crystalloids during the pre-ICU (nonprotocol-driven) phase of the resuscitation. As we described earlier, the normal DO$_2$I resuscitation goal resulted in the same response in terms of cardiac index and mixed venous oxygen saturation (Figure 1). Supranormal and normal resuscitation optimized the arterial base deficit and serum lactate during a similar time frame (Figure 2). To achieve the supranormal goal, significantly more crystalloid volume infusion was required, and there was a tendency toward more packed red blood cell transfusion (P = .07) (Figure 3). The UBP of the supranormal cohort was significantly higher at 4 hours after ICU admission and remained higher throughout the first 24 hours (Figure 4A). The gastric regional perfusion described by the GAP$_{CO}_2$ was higher in the supranormal group (Figure 4B). The supranormal cohort experienced worse outcomes, with higher frequency of IAH, ACS, MOF, and mortality (Table 2).

### RESULTS

Data are presented as mean ± SEM. Data were analyzed using an analysis of variance, $\chi^2$, and $t$ tests. The analysis of variance was used to analyze and compare time sequence data between the 2 cohorts. The $\chi^2$ test was used to compare the injury severity score between the male and female cohorts, a non-parametric scale assessment. $t$ tests (unpaired, 2-tailed) were used to compare parametric quantities (eg, clinical laboratory measurements, fluid volumes, and stay times). A difference between or within the supranormal and normal cohorts with $P<.05$ was considered significant.
We have learned from a small group of age-matched shock trauma patients that normal and supranormal resuscitation can yield the same physiologic response to the standardized shock resuscitation protocol. It was clear from this study that with supranormal resuscitation, significantly more LR was infused. There was
Urine Output
Venous Crystalloids

Diagnosis and Medical Management of Acute Renal Failure

In summary, our standardized shock resuscitation protocol provided a unique opportunity to compare se-

Figure 4. A, Urinary bladder pressure of patients on supranormal and normal resuscitation. B, Gastric regional mucosal carbon dioxide minus end-tidal carbon dioxide (GAPCO2) of patients on supranormal and normal resuscitation. DO2i indicates oxygen delivery index; UBP, urinary bladder pressure.

Table 2. Outcomes of the Supranormal and Normal Resuscitation Cohorts

<table>
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<tr>
<th></th>
<th>Supranormal Resuscitation (n = 85)</th>
<th>Normal Resuscitation (n = 71)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-abdominal hypertension</td>
<td>42†</td>
<td>20</td>
</tr>
<tr>
<td>Abdominal compartment syndrome</td>
<td>16†</td>
<td>8</td>
</tr>
<tr>
<td>Multiple organ failure</td>
<td>22†</td>
<td>9</td>
</tr>
<tr>
<td>Death</td>
<td>27†</td>
<td>11</td>
</tr>
</tbody>
</table>

Data are given as percentage of patients. †P<.05.

Figure 5. CO indicates cardiac output; IAP, intra-abdominal pressure; PCWP, pulmonary capillary wedge pressure; +, positive effect; −, negative effect; and ACS, abdominal compartment syndrome.

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vely injured patients in shock who were resuscitated with supranormal or normal DO2I goals. The review of the prospective resuscitation data demonstrates that supranormal resuscitation, compared with normal resuscitation, was associated with more LR infusion, decreased intestinal perfusion (higher GAPCO2), and an increased incidence of IAH, ACS, MOF, and death.

Accepted for publication February 23, 2003.

This study was supported by grants P50 38529-11 and U54 GM62119-01A1 from the National Institute of General Medical Sciences, Bethesda, Md.

This study was presented at the 110th Scientific Session of the Western Surgical Association, Vancouver, British Columbia, November 20, 2002, and is published after peer review and revision. The discussions that follow this article are based on the originally submitted manuscript and not the revised manuscript.

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DISCUSSION

Donald E. Fry, MD, Albuquerque, NM: The authors have pre-

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tive period and, for that matter, during the entire period of patient management in the critical care unit after major injury.

So I would like to offer 3 questions to the authors. What in fact were the postresuscitative hemoglobin differences in the 2 groups of patients? I would suspect that at 24 hours, those differences were significant. Can the authors tell us now that they have abandoned hyperoxygenation as a strategy? What did they shoot for as the appropriate hematocrit in the postresuscitative patient? This inevitably draws enormous debate in our institution every time this subject is discussed.

Finally, I would actually question the value of the routine placement of the pulmonary artery catheter of the Swan-Ganz catheter as was apparent that they did through this study. If you are not going to calculate oxygen delivery and if the majority of patients in fact can be appropriately resuscitated with clinical criteria that they used, do they continue to recommend that postresuscitative trauma patients, that trauma patients going into the intensive care unit, really require the pulmonary artery catheter? There continues to be some debate whether the pulmonary artery catheter itself may in fact be a source of morbidity, and I would be interested in their reflections on that.

Steven Stain, MD, Nashville, Tenn: My question relates to Dr Fry’s comments. The end point of resuscitation in both groups was oxygen delivery, and that requires a Swan Ganz catheter for calculation. If you have a relatively young trauma patient with an ISS (injury severity score) greater than 15 who requires blood transfusion for a splenectomy, does that patient also require a Swan or can that patient be managed just with urine output and clinical criteria?

Gregory Jurkovich, MD, Seattle, Wash: Ten years ago, we were encouraged to use supranormal oxygen delivery to drive our care during the initial resuscitation of critically injured patients. In this short time period, not only has this been questioned, but this paper refutes it as not only being of no benefit but also of being harmful.

Dr Fry has emphasized the importance of and questions the relative hemoglobin or hematocrit that should be idealized in the circulation during resuscitation. I want to add to that question my concern for what now should be the appropriate measure of adequacy of resuscitation. You have argued that a delivery of oxygen of greater than 600 mL/min would be inappropriate and that 500 mL/min is the same. But is there another number that is better? Is 400 okay; is 300 okay? What is and what should be our end point of resuscitations? Particularly bothersome to me is that the SVO₂, my preferred measure of adequacy of resuscitation, was the same in both of these groups. So I am perplexed now as to what I should use as a resuscitation end point or resuscitation goal. I would appreciate your comments on what you now use to determine effective resuscitation.

Dr Cocanour: We are using a computerized resuscitation protocol. One of its strengths is that it allows us to do these kinds of studies and decrease the variability between groups even though this study was done over 2 consecutive periods of time. Other than the drop in DO₂I, the protocol did not change.

What was the difference in the postresuscitation hemoglobin between the 2 groups? We did not include it in the manuscript or presentation but it was similar to the transfusion data, which, if you remember, the P value was only .07. There was a slightly higher hemoglobin at postresuscitation in those who had a DO₂I of 600 as a goal. We will need to go back and review the actual numbers.

What is the appropriate hemoglobin goal for resuscitation? We still have arguments within our own group. I am not sure that anybody knows for sure. I am satisfied with a hemoglobin above 7 or 8, although if someone is bleeding, you need to keep the hemoglobin higher to avoid having the next hemoglobin come back at 4. It also must be individualized for each patient.

What is the appropriate hemoglobin goal for resuscitation? Again, there is still a great deal of controversy about this. It will take many more studies before we can definitely say what is an appropriate hemoglobin.

Yes, we still are using PA [pulmonary artery] catheters. The senior author feels that this is the gold standard for being able to monitor oxygen delivery, and oxygen delivery is still one of the best resuscitation end points. We have looked at using other devices as well. We have not come up with anything that we really like better, so we are still using the PA catheter.

What about the young, healthy patient who has had a splenectomy? These patients usually don’t get put on the resuscitation protocol. We didn’t go over the criteria for placement into the resuscitation protocol in depth, but if someone is not going to require an additional 6 units of blood over the next 24 hours, and their base deficit is corrected, I see no need to put those patients on the resuscitation protocol. But for patients with pelvic fractures from blunt trauma who are going to continue to lose blood, patients with continued oozing from raw surfaces in the abdomen or chest, or those in whom the base deficit is not correcting, these are the patients most likely to benefit from being placed on the resuscitation protocol.

What is the appropriate end point of resuscitation? If anybody ever comes up with an easily measured and appropriate end point that works for every single different patient, they will probably be able to make a lot of money. I don’t know what the appropriate end point is. We have gone from a DO₂I of 600 because we noticed that a noticeable number of patients developed pulmonary edema during the resuscitation process, so as a consequence, our group dropped it to 500, and whether or not we should drop it further, I don’t know. I really am not sure what the appropriate end point is if you are using DO₂I. I also do not know of anything better at this point.