A New Resource-Constrained Triage Method Applied to Victims of Penetrating Injury

William J. Sacco, PhD, D. Michael Navin, MS, Robert K. Waddell II, EMT-P, Katherine E. Fiedler, PhD, William B. Long, MD, FACS, and Robert F. Buckman Jr, MD, FACS

Background: Resource-constrained triage occurs when the number of trauma patients exceeds the capacity for simultaneous transport and treatment. The objective of this article is to apply a new resource-constrained triage method (denoted Sacco triage method [STM]) to victims of penetrating trauma and compare it with existing methods.

Methods: STM is a mathematical model of resource-constrained triage. Its objective is to maximize expected survivors given constraints on the timing and availability of resources. The model incorporates estimates of time-dependent victim survival probabilities based on initial assessments and expected deteriorations. For application to penetrating trauma, an "RPM" score based on respiratory rate, pulse rate, and best motor response was used to predict survivability. Logistic function-generated survival probability estimates for scene values of RPM were determined from 7,274 penetrating injury patients from the Pennsylvania Trauma Outcome Study. The Delphi Method provided expert consensus on victim deterioration rates, and the model was solved using linear programming. The accuracy of predicting survivability was assessed using calibration and discrimination statistics. STM was compared with START (Simple Triage and Rapid Treatment)-like triage methods with respect to process and outcomes (assessed by expected number of survivors in simulated resource-constrained casualty incidents).

Results: RPM was shown to be an accurate predictor of survival probability for penetrating trauma, equivalent to the Revised Trauma Score and exceeding that of the Injury Severity Score, as measured by calibration and discrimination statistics. In the simulations, STM had substantially more expected survivors than did current triage methods.

Conclusions: Resource-constrained triage is modeled as an evidence-based, outcome-driven method (STM) that maximizes expected survivors in consideration of resources. STM offers lifesaving and operational advantages over current methods.

Key Words: Triage, Trauma, Scoring, Disaster, Mass casualty, Constrained resources.

J Trauma. 2007;63:316–325.

Triage is the process of assigning treatment and evacuation priorities to patients. Its introduction by Baron Larrey during the Napoleonic Wars (circa1812) has been well documented.[1] We think that in the nearly 200 years since its introduction, however, there has not been a rigorous, scientific formulation of triage. In an earlier article,[2] we presented what we thought to be the first evidence-based and outcome-driven triage method (denoted Sacco triage method [STM]) for resource-constrained triage and applied it to victims of blunt injury. The goal of the method is to maximize the expected number of survivors in consideration of the timing and availability of resources. In April 2005, the Agency for Healthcare Research and Quality (AHRQ) produced a report entitled *Altered Standards of Care in Mass Casualty Events*, which compiled the findings of a committee

of mass casualty experts (http://www.ahrq.gov.altstand/altstand.pdf). Their first finding, "the goal of an organized and coordinated response to a mass casualty event should be to maximize the number of lives saved", matches the STM goal. (See Discussion for further review of STM in consideration of the AHRQ report.) In this article, we apply STM to resource-constrained triage involving victims of penetrating injury.

Limitations of Current Triage Methods and the Criticality of Emergency Medical Service Preparedness and Response Motivate This Research

The most widely used triage method is called START (Simple Triage and Rapid Treatment).[3–9] START and START-like methods help organize victims at a casualty scene, and have the goal of "doing the greatest good for the greatest number". They propose sorting victims into four categories: immediate, delayed, expectant, and ambulatory. Immediates are those deemed critically injured and require immediate intervention. Delayeds are those injured "but not expected to die within the first hour if care is delayed". Expectants are patients who are presumed deceased, or have catastrophic injuries, and survival is not expected. Ambulatory patients can walk and are presumed not critically injured. The START strategy is to treat immediates first, then delayeds, then others as possible. In practice, providers often try

to treat the worst first within each category as this is consistent with the protocol: "By triaging patients, you will be able to concentrate first responder resources on the most seriously injured" (http://www.start-triage.com/START_TRIAGE.htm). START uses a sequence of three physiologic screens—respirations, pulse or perfusion, and mental status—to classify victims as immediates or delayeds.

START and START-Like Methods Have Scientific Limitations

1. The goal of "doing the greatest good for the greatest number" is imprecise. There is no measure of outcome, and results cannot be replicated.
2. There is no consideration for resource availability. Immediates are transported first irrespective of the resources available. As a result, the START triage strategy for a 20-victim incident, for example, is the same whether there are 2 ambulances or 10.
3. There is no differentiation between victim severities within categories, although the severities within immediates and delayeds can vary widely. Also, there can be significant severity overlap between immediates and delayeds (see Results).
4. Victim survival probability is not considered explicitly when triaging victims.
5. There is no consideration for or differentiation among trauma types.

These limitations lead to subjective and extremely inconsistent triaging. As documented in *Triage is Broken*,[10] even providers with the same START training can make radically different triage choices. In tabletop exercises, a simulated victim deemed the top priority for transport and treatment by one emergency medical service (EMS) provider team is often ranked as the lowest priority by other teams. Comparison across teams shows that triage appears almost as a random ordering of victims. "Surprisingly, there has been very little research validating or even evaluating these systems", says Dr. David Cone.[11] "We simply have no idea whether any of them actually work as intended, or have any effect on patient outcome even if used as designed". These issues have motivated us to formulate the triage problem precisely and mathematically.

PATIENTS AND METHODS
Mathematical Formulation of Resource-Constrained Triage

The resource-constrained triage problem is formulated mathematically. The goal is to maximize the expected number of survivors, subject to constraints on the timing and availability of transport and treatment resources. To maximize expected survivors, we need predictions of survival probability and changes in survival probability over time (i.e., deterioration). We assume that a SCORE value can be computed based on each victim's severity that is predictive of survival probability. We further assume that deterioration

over time can be estimated for each SCORE value. For simplicity, we present a formulation that does not include treatment resources explicitly.

Let $V_{s,t}$ = the number of victims treated in time period t whose original (first assessment) SCORE is s.

$P_s(t)$ = the survival probability of victims with an original SCORE of s treated in time period t.

n_s = number of victims whose original (first assessment) SCORE value is s.

R_t = maximum number of victims that can be transported in time period t.

$s = 0, 1, \ldots, S; t = 1, 2, \ldots, k.$

The objective is to maximize expected survivors:

$$\text{Max}\{[P_0(1)V_{0,1} + P_1(1)V_{1,1} + \cdots + P_{12}(1)V_{12,1}]$$
$$+ [P_0(2)V_{0,2} + P_1(2)V_{1,2} + \cdots + P_{12}(2)V_{12,2}]$$
$$+ \cdots + [P_0(k)V_{0,k} + P_1(k)V_{1,k} + \cdots + P_{12}(k)V_{S,k}]\},$$

(1)

subject to constraints on transport resources (A) and on victims at the scene (B):

$$V_{0,1} + V_{1,1} + \cdots + V_{12,1} \leq R_1$$
$$V_{0,2} + V_{1,2} + \cdots + V_{12,2} \leq R_2$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A)}$$
$$V_{0,k} + V_{1,k} + \cdots + V_{12,k} \leq R_k,$$

and

$$V_{0,1} + V_{0,2} + \cdots + V_{0,k} = n_0$$
$$V_{1,1} + V_{1,2} + \cdots + V_{1,k} = n_1$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(B)}$$
$$V_{S,1} + V_{S,2} + \cdots + V_{S,k} = n_S$$

Formulation Fits Linear Programming Structure; Can be Solved Efficiently

This model is a linear programming formulation[12] of resource-constrained triage. Problems that fit a linear programming structure can be solved efficiently by the simplex method,[12] even for large-scale problems, using commercial software. Linear programming and the simplex method are well documented and extensively used mathematical methods for solving combinatorial problems that have linear objective functions and linear constraints.

The output of the linear program is the triage strategy, which specifies the order in which victims are to be transported and treated. The output identifies the number of victims with each score and each time period to be transported, treated, or both such that the expected number of survivors is the maximum possible, given limitations on resources. The simplex method provides solutions in seconds even for mass

casualty situations, and can be recomputed in response to scene and resource changes.

The formulation reflected above is generic. SCORE can be any measure used to characterize victim severity and a related estimate of survival probability. It may depend on the type of trauma or toxic insult (blunt, penetrating, blast, burn, etc.), the nature of the injuries, and the physiologic response to the insult.

Formulation is Flexible and Can Be Extended

The generic linear programming formulation has been extended in the software implementation of the algorithm to account for (1) treatment classes, such as trauma and non-trauma centers; (2) treatment capacities by facility; and (3) transport capacity by mode of transport.

Application of the Model to Victims of Penetrating Injury

Three methods are used to adapt the formulation to victims of penetrating injury. A physiologic SCORE is used to predict survivability of such victims. Evidence-based survival probability estimates are determined for each SCORE value using logistic regression. Experts estimate deterioration rates for each SCORE value primarily using the Delphi Method. Each method is explained below.

RPM is Used to SCORE Victim Severity

STM requires estimates of survival probability for each casualty. The chaos of the incident scene dictates that the SCORE be quickly and easily obtained. The SCORE we use for casualties with penetrating injuries is RPM,[2,13–15] which incorporates *r*espiratory rate (RR), *p*ulse rate (PR), and best *m*otor response (BMR). RPM is the sum of coded values for RR, PR, and BMR.

RPM takes on integer values from 0 to 12. RR is assessed in breaths per minute and PR is assessed in beats per minute. BMR assesses the ability of the casualty to respond with movement to pain or verbal stimuli and is similar to how it is computed within the Glasgow Coma Scale. As detailed by Sacco et al.,[2] the use of BMR here combines flexion and extension for the same coded values, and also provides an enhancement when the patient is a preverbal child.

Logistic Regression Used to Determine RPM-Based Survival Probability Estimates

The application of the formulation to victims of penetrating trauma uses survival probability estimates obtained from retrospective analysis of data from trauma centers in the Pennsylvania Trauma Outcome Study (PTOS), a statewide trauma center registry. Of the 8,357 patients with penetrating injuries in the database from 1986 to 2002, we included only nontransfer patients with complete scene RPM values exclusive of patients intubated at the scene before assessment of RR or BMR. Intubation often precludes accurate respiratory

or neurologic assessments and is seldom done in mass casualty events. The study included the remaining 7,274 patients.

The study patients were divided into two sets. The logistic coefficients were derived on a Design Set, and validated on a Test Set: Design Set, every other survivor and every other nonsurvivor through the entire database (3,637 patients); Test Set, the remaining 3,637 patients in the set of 7,274 patients. The Design Set was used to obtain a logistic function for estimating survival probabilities based on scene RPMs. Here the logistic function has the form

$$P_s = 1/(1 + e^{-w}),$$

where P_s is the survival probability estimate, and

$$w = w_0 + (w_1 \times RPM).$$

Logistic function-generated survival probability estimates were determined using SAS, version 8 (SAS Institute, Inc., Cary, NC) for incident scene RPM values. Logistic regression coefficients (w_0, w_1) obtained from the Design Set were used to estimate survival probabilities for patients in the Test Set. The logistic function predictive performance was assessed using concordance (C)[16] (which measures the ability of a scoring system to distinguish survivors and deaths) and a Normalized Hosmer-Lemeshow (NHL) statistic[2] (which evaluates the degree of agreement between the actual number and score-predicted number of survivors and deaths in various risk strata). A concordance value of 0.5 indicates no predictive discrimination, and a value of 1.0 indicates perfect separation of survivors and nonsurvivors. The closer C is to 1.0, the better the discrimination value is considered to be.

We also computed for the Total Patient Set (Design and Test Sets combined), the logistic function weights, C, NHL, and the survival probability estimates for each RPM value. The survival probability estimates for the Total Patient Set are those used in the STM model.

Delphi Technique Used to Estimate Victim Deterioration

Change in survival probability estimates for victims who remain at the incident scene were obtained using the Delphi technique.[17,18] The Delphi technique is a method for achieving consensus estimates among a group of experts when empirical evidence is unavailable or insufficient.

In our application, the Delphi technique was used to obtain a consensus among 11 trauma care experts (see Acknowledgments) regarding estimates of changes in RPM values for victims presumed to receive little or no treatment while awaiting transportation to a higher level of care. Each expert provided estimates of scene RPM value changes in 30-minute increments during a 6-hour period, and a rationale for the estimates. The estimators were to presume that minimal care could be provided by emergency responders. For example, a victim may have his or her airway opened or receive a pressure bandage to control bleeding, but resources

would not be available to provide continuous intravenous fluids or other invasive therapeutic interventions.

Anonymous estimates and rationales for all estimators were shared with the participants, and a second round of estimates was requested. This second set of estimates was used to compute median changes in RPM values (denoted as Delphi estimates) for successive time periods for each initial RPM value.

Institutional Review Board Approval Deemed Unnecessary

The authors did not have access to patient identifiers nor to trauma center identifiers. The study was determined to be exempt from institutional review board consideration as advised by the Pennsylvania Trauma Systems Foundation, as the data neither identifies the patient, nor the participating hospital.

Implementation of STM for Penetrating Trauma

Operational implementation of STM is defined here in sufficient detail for comparison of STM with START. It is not the intent to provide exhaustive details on the software and other implementation materials. A more detailed description of the implementation was provided in "A disaster doesn't have to be a disaster: an evidence based method that 'takes the guesswork out of triage' ".[19]

Scoring and Tagging of Victims

Victims are scored and tagged (a score-based tag is used), and then organized at the scene into score groups. The groups are more homogeneous than those for START with respect to survival probability and expected deterioration, and enable a more qualified use of scene medical resources. Scoring of victims is supported by the use of reference cards or personal data assistants (PDAs).

Victim RPM values are communicated to incident command or a central dispatch facility, and the linear programming model is applied. The time for inputting scores, running the linear program, and communicating the triage strategy back to the scene takes less than 1 minute in simulations. The output from the software is the optimal triage strategy for current conditions and a regional resource plan. The plan, publishable to the Web, shows the number of transport units needed; the estimated time to move all victims to treatment facilities; the treatment facilities impacted; and the number, severity, and scheduled arrival of all victims that each facility will receive. These reports can be provided live during an incident, and can be broadcast to a secure Web site for access by local, regional, and even federal EMS or other agencies. The software readily accommodates scene and resource changes throughout an incident, and balances the patient load among treatment facilities.

Table 1 Concordance (C) and Normalized Hosmer-Lemeshow (NHL) Statistics for Scene RPM Values

	C	HL	Patients (n)	NHL (HL/Patients)
Design Set	0.94	54	3,637	0.015
Test Set	0.94	66	3,637	0.018
Total Set	0.94	98	7,274	0.013

Process and Outcome Comparisons of STM and START

As the intent of this research is to provide decision support tools for resource-constrained triage, a comparison with START includes practical and conceptual considerations. We review the goal of each method, the triage decision-making process and considerations, the resulting triage strategy, and operational considerations such as ease of use, accuracy, and speed. We also compare outcome through a series of simulations. The linear programming software used for the simulations was LINDO/PC, Release 6.1 (Lindo Systems, Inc., Chicago, IL).

RESULTS
RPM Survival Probability Estimates are Accurate

The logistic function for estimating survival probabilities is

$$P_s = 1/(1 + e^{-w}),$$

where P_s is the survival probability estimate and

$$w = w_0 + (w_1 \times RPM).$$

The weights, w_0 and w_1, computed for the Design Set, were −5.0430 and 0.7214. These were used to compute survival probabilities for each RPM value, and to compute C, HL, and NHL for the Design Set and for the Test Set (Table 1). The C, HL, and NHL values are strikingly similar for the Design and Test Sets, indicating that the weights determined for the Design Set accurately extend to the Test Set.

Since this "test" was passed, the logistic weights $w_0 = -5.1153$, and $w_1 = 0.7265$, were computed based on the Total Patient Set and used to generate survival probabilities (Table 2). These probabilities are those used in the STM model. The C, HL, and NHL values for the Total Set (also shown in Table 1) indicate that the survival probability estimates are good predictive values. For practical comparisons, the Total Set C value for RPM (0.94) is nearly that for the widely used Revised Trauma Score[20] (C = 0.95) and exceeds that for the Injury Severity Score[21] (C = 0.86). The Total Set HL value of 98 for RPM is slightly less (less is better) than that for the Revised Trauma Score (HL = 100) and much less than that for the Injury Severity Score. The comparison of RPM and Injury Severity Scale (ISS, an anatomic index) was included solely to give perspective on the predictive value for RPM. ISS is not interchangeable with RPM for triage purposes.

Table 2 Probability Survival Estimates for Scene RPM Values

RPM Value	Design Set	Total Set
12	0.97	0.97
11	0.95	0.95
10	0.90	0.90
9	0.81	0.81
8	0.67	0.68
7	0.50	0.49
6	0.33	0.32
5	0.19	0.19
4	0.10	0.10
3	0.053	0.050
2	0.027	0.025
1	0.013	0.012
0	0.0064	0.0060

Delphi Estimates of Victim Deterioration

Table 3 contains the Delphi estimates of patient deterioration assuming minimal patient care. The time periods are 30-minute intervals after the initial RPM assessment. As an example, a victim with an initial RPM of 12 is expected to remain a 12 for 1.5 hours (i.e. through time period 2), before dropping to an 11 for the next hour, then a 10 for 2 hours, etc. Table 3 shows interesting (though intuitive) results. Victims whose survival probability exceed 0.80 (those with RPMs >9), deteriorate slowly, as one might expect. Victims with RPMs <5 have survival probabilities <0.11 and fall quickly, although they do not have far to fall. Victims in the middle range of severity (RPMs 5–8) can decline rapidly also.

STM Dominates START in Process and Outcome

After separating "walking wounded" and "expectants", START uses physiologic screens to categorize and group victims into immediates and delayeds, then assigns all immediates first to transport and treatment. STM uses an RPM value for each victim, then organizes victims by RPM groups (i.e., 0–4; 5–8; 9–12), and communicates RPM values to incident command or a central dispatch facility, where an optimal triage strategy is determined based on scene and resource inputs.

Process and Outcome Comparison of START and STM
Process Comparison

STM mitigates the limitations of START:

● STM's goal to maximize the expected number of survivors is explicit, measurable, and outcome driven. For an actual casualty incident, a simulated incident, or even a disaster exercise, EMS performance and projected or actual outcome can be evaluated. START's goal of "doing the greatest good for the greatest number" is imprecise, and not measurable.

● START's sorting process is simple, but inaccurate. With penetrating trauma, a START immediate can have RPM values from 1 to 11 (survival probability ranging from 0.012 to 0.95). START's delayeds RPM values range from 6 to 12 (survival probability ranging from 0.32 to 0.97). Thus, the overlap in survival probability between immediates and delayeds can range from 0.32 to 0.95.

● START's triage strategy requires the subjective selection of patients within the broad categories of immediates first, and then delayed, independent of resource levels. As detailed in *Triage is Broken*,[10] the resulting strategy is extraordinarily inconsistent and nonreproducible. STM explicitly considers evidence-based survival probabilities, estimated deterioration rates, the timing, and availability of transport and treatment resources, and the number and physiology of victims. The resulting triage strategy is a precise priority assignment of victims to treatment.

● START is easy to learn, though difficult to remember, as its use is limited to mass-casualty situations and drills. STM also is easy to learn and easy to retain if used, as we propose, for routine trauma calls and patient outcome tracking.

● START assessments are quicker than are those for STM. Determining if a patient is immediate or delayed typically takes about 30 seconds. Obtaining an RPM value

Table 3 Delphi Estimates of RPM Values in 30-Minute Intervals

Initial RPM	Time Intervals											
	1	2	3	4	5	6	7	8	9	10	11	12
12	12	12	11	11	10	10	9	9	9	8	8	8
11	11	11	10	10	9	8	7	7	7	6	5	5
10	10	9	9	8	8	7	6	5	5	5	4	4
9	9	8	8	7	5	4	3	1	0	0	0	0
8	7	6	4	3	3	2	2	0	0	0	0	0
7	6	5	3	1	0	0	0	0	0	0	0	0
6	4	3	2	1	0	0	0	0	0	0	0	0
5	3	2	0	0	0	0	0	0	0	0	0	0
4	2	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

typically takes about 45 seconds. Both START and RPM assessments use 15-second counts for respiration and pulse.

● STM promotes better use of scene medical resources as victim groupings are homogenous by survival probability, whereas START's immediate range in survival probability from 0.012 to 0.95. STM suggests three groupings: RPMs of 0 to 4 with survival probabilities of less than 0.11 and expectations of rapid and fatal deterioration; RPMs of 5 to 8 with corresponding survival probabilities of 0.19 to 0.68 with accelerating deterioration expectations; and RPMs of 9 or greater with survival probabilities greater than 0.80 and slow expected deterioration.

● For optimal results, STM requires software support, communication to incident command or central dispatch, and resource availability information. In trials, scene-to-dispatch communication typically takes less than 60 seconds, including the running of the linear programming software that creates the triage strategy. Resource information can be updated off line from scene communication. START does not require technology, communication, scene information, or resource information. (Note: STM is used to generate a sub-optimal rule-based protocol to guide triage decisions in the absence or failure of communications. The rules are developed a priori through simulations of a regions likely mass casualty threats and EMS capabilities.)

Outcome Comparison

Simulated multiple casualty incidents were evaluated to compare outcomes of STM and START. Because START does not measure outcome, nor provide guidance on ordering victims within each category, we assume all possible orderings within these categories, and present outcome by range. We also present the outcome of a "worst-first" strategy (among nonexpectants), which is consistent with START guidelines.

Three sets of five simulations of 60 victims are presented (Table 4). All sets have the same five distributions of victim severity: (1) immediates only; (2) equal mix of immediates and delayeds; (3) twice as many immediates; (4) twice as many delayeds; and (5) delayeds only.

In set 1, we assume resources sufficient to transport 20 victims per 30 minutes. In set 2, we assume a more resource-constrained environment (e.g., when access or egress is re-

stricted) and a reduced transport rate of 10 victims per 30 minutes. In set 3, we assume severe resource limitations (e.g., rural setting) and a transport rate of six victims per 30 minutes. For simplicity of the simulations, and although we know there is wide overlap between START immediates and delayeds, all immediates are assumed to have lower RPM values than all delayeds.

As shown in Table 5, STM dominates START outcome in all cases and the savings increase as resources are tightened. There are significant and noteworthy trends in the performance of each method, and in comparisons between the methods.

Observations About the START Simulation Outcomes

● START's outcomes tended toward the low end of the projected survivor range when START promotes "worst-first" ordering. As the care providers cannot identify worst-first victims with certainty, one would expect START's solution to be toward but not at the "worst-first" solution.

● The range of possible outcomes with all immediates (i.e., simulation 1 of all sets) is large as all possible victim orderings are included. This is because START does not guide triage within categories. The chance of START "randomly" achieving the optimal solution for simulation 1 is infinitesimal.

● In simulations with both immediates and delayeds (i.e., numbers 2, 3, and 4 of all sets), START cannot randomly achieve the optimal triage strategy, as the optimal strategy requires that some delayeds have priority over some immediates.

● START strategy works best when there are only delayed victims (i.e., simulation 5). Across all three sets, the worst-first ordering either matches or is near the optimal strategy; however, this requires that victims can be ordered as worst-first within the delayed category.

● In set 3 with severe resource limitations, worst-first triage is inefficient as scarce resources are continually applied to victims with little chance of survival, at the expense of the deterioration of remaining victims.

Observations About the STM Simulation Outcomes

● Notice that the STM triage strategy is consistent in this entire family of simulations, in which individuals with RPMs of 8, 7, and 6 favored for early transportation, especially in simulations that involve only victims with values 2, 3, 4, 6, 7, and 8.

● For the five simulations of set 1, STM achieves, respectively, 81%, 81%, 84%, 77%, and 94% of the "maximum expected survivors with unlimited resources" (which assumes all victims are transported within the first time period). This is so even though set 1 simulations assume 90 minutes to transport all victims.

● The changes in STM strategy in response to resource changes mitigates the impact of declining resources.

Table 4 Simulation Distributions

Distribution Number	STM Categories	START Categories
1	10 each: 2, 3, 4, 6, 7, 8	All immediate
2	10 each: 2, 3, 4, 6, 7, 8	Immediate Delayed
3	14 each: 2, 3, 4	Immediate
	6 each: 6, 7, 8	Delayed
4	6 each: 2, 3, 4	Immediate
	14 each: 6, 7, 8	Delayed
5	10 each: 6, 7, 8, 9, 10, 11	All delayed

Table 5 Simulation Results

Victims Severity Distribution*		START Category	Expected Survivors (START), Max–Min	Worst-First Expected Survivors	Expected Survivors STM	STM Triage Order by RPM Time up to 30; 60; 90; 120; 150 min	Maximum Expected Survivors With Unlimited Resources
Victim	RPM						
Set 1: 60 victims, transport rate 20 victims per 30 min (urban or abundant resources)							
10 each	2, 3, 4	All					
10 each	6, 7, 8	Immediate	13.5–7.1	8.8	13.5	8, 6; 7, 4; 3, 2	16.7
10 each	2, 3, 4	Immediate					
10 each	6, 7, 8	Delayed	8.9–7.1	7.1	13.5	8, 6; 7, 4; 3, 2	16.7
14 each	2, 3, 4	Immediate					
6 each	6, 7, 8	Delayed	5.2–4.4	4.4	9.6	8, 7, 6, 4; 4, 3; 3, 2	11.4
6 each	2, 3, 4	Immediate					
14 each	6, 7, 8	Delayed	12.7–11.0	11.0	16.9	6; 8, 7; 6, 4, 3, 2	21.9
10 each	6, 7, 8	All					
10 each	9, 10, 11	Delayed	38.9–32.7	38.7	38.9	8, 6; 9, 7; 11, 10	41.5
Set 2: 60 victims, transport rate 10 victims per 30 min (access/egress restrictions)							
10 each	2, 3, 4	All					
10 each	6, 7, 8	Immediate	10.5–1.2	1.4	10.5	8; 7; 6; 4; 3; 2	16.7
10 each	2, 3, 4	Immediate					
10 each	6, 7, 8	Delayed	2.3–1.2	1.4	10.5	8; 7; 6; 4; 3; 2	16.7
14 each	2, 3, 4	Immediate					
6 each	6, 7, 8	Delayed	1.6–0.8	0.9	7.7	6, 8; 8, 7, 4; 4, 3; 4; 2; 2, 3	11.4
6 each	2, 3, 4	Immediate					
14 each	6, 7, 8	Delayed	5.8–2.4	2.7	12.6	8; 8, 7; 7, 6; 6; 6, 4, 2; 2, 3	21.9
10 each	6, 7, 8	All					
10 each	9, 10, 11	Delayed	34.0–21.5	31.3	34.0	8; 7; 9; 10; 11; 6	41.5
Set 3: 60 victims, transport rate 6 victims per 30 min (sever limits or extrication or rural)							
10 each	2, 3, 4	All					
10 each	6, 7, 8	Immediate	8.1–0.3	0.3	8.1	8; 8, 7; 7; 7, 6; 6; 3, 2; 2, 4; 4; 3; 2	16.7
10 each	2, 3, 4	Immediate					
10 each	6, 7, 8	Delayed	1.2–0.3	0.3	8.1	8; 8, 7; 7; 7, 6; 6; 3, 2; 2, 4; 4; 3; 2	16.7
14 each	2, 3, 4	Immediate					
6 each	6, 7, 8	Delayed	0.9–0.2	0.2	6.3	8; 7; 6; 3;4, 2; 2; 3, 4; 4; 3; 2	11.4
6 each	2, 3, 4	Immediate					
14 each	6, 7, 8	Delayed	1.7–0.6	0.6	8.8	8; 8; 8, 7; 7; 7, 6; 6; 6; 4; 3; 2	21.9
10 each	6, 7, 8	All					
10 each	9, 10, 11	Delayed	28.5–12.6	15.3	28.5	8; 8, 9; 9; 9, 10; 11; 10; 11, 6; 6; 7; 7, 6	41.5

Comparison Between START and STM Within Each Set of Simulations

● In set 1, STM is projected to save as many as five additional victims in all simulations. In simulation 5, which includes only delayeds, the worst-first strategy is nearly optimal.

● In set 2, which has tighter resources, the maximum projected increase in survivors across the five simulations ranges from 7 to 12; whereas the minimum increase ranges from 0 to 8 ("0" assumes the START strategy, by chance, matches the optimal triage order).

● In set 3 with severe resource restrictions, the maximum projected increase in survivors across the five simulations

ranges from 6 to 16; whereas the minimum increase ranges from 0 to 7 (again, "0" assumes the START strategy, by chance, matches the optimal triage order).

Comparisons of START and STM Across the Sets of Simulations

● The changes in STM strategy, in response to resource changes, mitigates the impact of declining resources, whereas START's decrease in "survivorship" is dramatic. To illustrate, consider simulation 2. As resources decline from 20 to 10 to 6 per 30 minutes (recall victim processing rate per half hour is 20 for set 1, 10 for set 2, and 6 for set 3), STM's expected survivors decline from 13.5 to 10.5 to 8.1. The expected survivors decline

from 7.1 to 1.4 to 0.3 for the worst-first strategy, and if we assume START's performance is closer to the midpoint of its range of possible outcomes the decline is from 8 to 1.8 to 0.7. As resources are then cut to 60% of set 2 levels in set 3, STM has a reduction in expected survivors of about 25%, whereas START's reduction is about 70%.

These results are consistent with hundreds of resource-constrained simulations involving various numbers of victims, level of resources, and distribution of victim severity.

DISCUSSION

As evidenced by this and previous research that applied STM to victims of blunt injuries,[2] resource-constrained triage can be modeled precisely and has the potential to substantially increase survivors as compared with current triage methods.

Current triage methods do not use well-defined objectives, do not consider resources in making triage decisions, broadly sort victims into overlapping categories, and provide no guidance for triage within categories even though survival probabilities vary greatly. Results of current triage practices are not reproducible and outcomes cannot even be measured. Simulations show that the worst-first triage approach suggested by most current triage protocols is often the strategy that yields the fewest expected survivors—continually using scarce resources on patients with little chance of survival is done at the expense of patients with a greater chance of survival who will deteriorate without timely care.

STM, formulated as a linear programming problem, has a well-defined goal of maximizing the expected number of survivors using time-dependent estimates of victim survival probabilities and restrictions on transport and treatment resources.

With the addition of this article, STM has now been applied to both penetrating and blunt trauma based on analyses of data from the Pennsylvania Trauma Outcome Study, and has been shown through simulations to yield substantial improvements in expected survivors in resource-constrained triage when compared with existing triage methods. The reader is encouraged to evaluate this research in this light. The data supporting STM are not perfect, nor were they collected specifically to support this research, but the data elements that support evidence-based and optimal triage are now well defined, and collectable in support of advancing this research. Furthermore, operational questions need to be answered through prospective studies. Nonetheless, it is our contention that STM, applied in its current form, will save substantially more lives than existing triage practices would, will allow for the collection of data to further improve evidence-based triage, and will provide a way to measure triage outcomes.

STM Supports National Policy Initiatives in Emergency Preparedness and Response

STM is closely aligned with two recent policy initiatives concerning emergency preparedness and response. In the U.S. Department of Health and Human Services' *Altered Standards of Care in Mass Casualty Events* (AHRQ Publication No. 05-0043, April 2005), a national panel of experts were assembled by the Agency for Healthcare Research and Quality (AHRQ) to define a blueprint for mass casualty preparedness. Table 6 shows how STM directly addresses all of the nine key findings of this report. Likewise, the National Incident Management System report (Department of Homeland Security, March 2004) defines requirements such as measurable objectives, interoperability, scalability, and resource management that are not addressed by current protocols, but are fundamental components of STM.

Database Limitations and Improvement Opportunities

Because the database does not include patients that die at the scene or in transit to the hospital, the survival probabilities are overestimated, likely more significantly and proportionately for small RPM values. As the optimal triage strategy tends to set low priorities for victims with small RPMs (see Results), the impact of this may not be significant. Nonetheless, data on prehospital deaths should be collected and included in the correlations.

The deterioration rates, although based on Delphi-generated expert opinion, are subjective. The availability of deterioration data for extended time periods is unknown to us; however, these data could be collected in future mass casualty incidents.

Routine use of RPM Score Suggested for Preparedness and EMS Performance Measurement

The daily use of the RPM score on all trauma patients enables EMS performance measurement, and encourages targeted evaluation of EMS intervention performance across the spectrum of trauma severity. EMS professionals can use the same victim assessment procedure in mass and multiple casualty situations that they use routinely. The data collected enables prehospital and hospital outcome evaluation and performance tracking. Significant deviations in outcome from data norms might lead one to investigate and isolate the impacts of training, equipment, and treatment protocols on outcome for specific RPM clusters or ranges, or by specific service provider or treatment facility. "Best practices" might be more easily identified and quantified. Furthermore, collecting scene and outcome data will seed analyses that will lead to improvements.

Future Research

The generic form of the STM model applies to other types of trauma. Early results of current research have begun to show that RPM is a good predictor of survivability for blast overpressure injuries. A review by a chemical agent expert indicates, surprisingly, that STM, with RPM as the severity assessment, may also be applicable to some nerve agents, for which RPM would reflect "exposure", but this research needs to be advanced.

Table 6 AHRQ-STM Match

AHRQ Findings	Sacco Triage Method Capability
1. The goal of an organized and coordinated response to a mass casualty event should be to maximize the number of lives saved.	STM is formulated and modeled mathematically to maximize expected survivors in an MCI. With use of a simple physiologic score that predicts survival and deterioration, patients are triaged to maximize expected survivors, a measurable objective, in consideration of the timing and availability of transport and treatment resources.
2. Changes in the usual standards of health and medical care in the affected locality or region will be required to achieve the goal of saving the most lives in a mass casualty event. Rather than doing everything possible to save every life, it will be necessary to allocate scarce resources in a different manner to save as many lives as possible.	STM is formulated as a classic resource allocation problem. It utilizes all regional resources in response to an MCI, whether it involves several patients or thousands, and determines an optimal triage strategy that allocates scarce resources to maximize expected survivors.
3. Many health system preparedness efforts do not provide sufficient planning and guidance concerning the altered standards of care that would be required to respond to a mass casualty event.	STM preparedness planning and training is focused on factors and capabilities that impact maximizing expected survivors. STM can be used routinely—every day, on every trauma patient. This ensures field preparedness and enables routine outcome tracking. STM software also provides MCI simulation capabilities and surge analyses.
4. The basis for allocating health and medical resources in a mass casualty event must be fair and clinically sound. The process for making these decisions should be transparent and judged by the public to be fair.	STM provides an evidence based, precise, and objective solution for maximizing expected survivors. Detailed resource allocation and incident action plans explicitly support the objective, and are science based and reproducible.
5. Protocols for triage (i.e. the sorting of victims into groups according to their need and the resources available) need to be flexible enough to change as the size of a mass casualty event grows and will depend on both the nature of the event and the speed with which it occurs.	STM is scalable and provides the optimum triage strategy quickly regardless of incident size, and groups patients at the scene more precisely, according to physiology and survival probabilities. It accesses regional transport and treatment capacity as needed, distributes and balances patient loads within the EMS system, and determines the optimal triage strategy in response to the type, size, and location of the incident.
6. An effective plan for delivering health and medical care in a mass casualty event should take into account factors common to all hazards (e.g., the need to have an adequate supply of qualified providers), as well as factors that are hazard-specific (e.g., guidelines for making isolation and quarantine decisions to contain an infectious disease).	A battery of simulations across types and sizes of MCIs can be run quickly with STM software to show the impact of treatment capacity on lives saved, and to generate rule-based protocols to be used when communications are compromised. STM also includes hazard-specific scoring capabilities for penetrating, blunt, and blast overpressure trauma and research is underway on chemical insults, and for patient ages.
7. Plans should ensure an adequate supply of qualified providers trained specifically for mass casualty events. This includes providing protection to providers and their families (e.g., personal protective equipment, prophylaxis, ...).	Preparedness is enhanced by routine STM scoring by field providers on all trauma patients; routine MCI training of dispatchers or incident commanders through periodic 5-min software simulations; routine hospital use for score-based outcome tracking; and explicit outcome performance measurement in MCI exercises. Exercises have demonstrated that minimal training is required to significantly improve performance against the goal. This expands potential resources for patient assessors to include nonmedically trained responders and focuses preparedness resources for far more cost effective results.
8. . . . Addresses nonmedical issues . . .	STM is the first triage and resource management system (and protocol) to be formally evaluated by the NIMS Integration Center, FEMA/DHS, for NIMS compliance. STM complies with supporting Incident Command with management by objectives and performance measures, by providing a unified objective with aligned protocols and strategies that flow directly from these. Other NIMS areas explicitly supported include: resource management, advance preparedness planning, communications and information management, supporting technologies and ongoing management and continuous improvement.
9. Guidelines and companion tools related to development of altered standards of care in a mass casualty event are needed by, and would be extremely useful to, preparedness planners at the federal, state, regional, community, and health systems levels.	STM has been used in various exercises to demonstrate inaccurate patient assessments and triage by Start-like methods. STM provides triage tags, scoring aids including PDA software if appropriate, field materials, and incident command software to support implementation. The STM incident command software provides regional simulation capabilities for planning purposes, and also produces a regional impact plan at the onset of an incident.

MCI, mass casualty incident.

A specific application of STM includes it use for blunt and penetrating military-aged victims under Office of Naval Research Contract N00014-05-C-0300. An article on this is being readied for publication.

Technologic advances might have significant impact on the scoring mechanism and efficiency. The impact of automation can improve the accuracy of the SCORE, and the amount of information that is used to compute a SCORE. PDA technology improves the accuracy of scoring, enables more sophisticated scoring, and also enables automated communication with dispatch for transmission of scene and strategy information. Remote sensors of vital signs are already under development by the military and can enable quicker and safer assessment of victim physiology and real-time measurement of deterioration.

Practical Considerations of STM

STM requires communication support for explicit model application and determination of optimal triage strategies. In

the absence of effective communication or technology support, good suboptimal rule-based versions of STM can be devised that consider survivability and broad resource levels to determine triage order. The rule-based protocols are best determined through simulations that reflect a region's EMS capabilities, including the proximities and capabilities of treatment facilities, as well as the likely threats faced by the region. Once the rule-based protocols are determined, they are provided on a pocket reference card and on a PDA, if appropriate, enabling the application of specific triage rules by type and size of incident.

Rule-based versions of STM are offered as a backup for nonexisting or failed communications technology. The performance of this rule-based adaptation exceeds that of current triage methods, and will be the subject of future publications. It is mentioned here to allay concerns that a technology failure would render STM ineffective.

CONCLUSIONS

A precise mathematical formulation was presented for resource-constrained triage. Based on a SCORE of each victim that is predictive of survival probability and rate of deterioration, scarce transport and treatment resources can be allocated and scheduled optimally, maximizing the expected number of survivors. This formulation was applied to penetrating trauma. Using data on 7,274 victims of penetrating trauma from the PTOS database, an RPM score was shown to be an accurate predictor of survival as measured by concordance and discrimination statistics. A Delphi method was used to devise a consensus among experts on expected deterioration rates, and the model was shown, through simulations, to offer considerable increases in lives saved as compared with START, the most widely used mass casualty triage method.

We acknowledge opportunities to improve the model, yet encourage practitioners to evaluate this research in comparison to existing methodologies, in consideration of positive implications for public health, and in recognition of advances that will undoubtedly come through prospective studies, targeted data collection, and outcome tracking. Implementation outcomes will include empirical validation of deterioration rates, the extension of the methodology to other types of trauma, and trauma care improvements resulting from routine EMS performance evaluation.

REFERENCES

1. Rignault D, Wherry D. Lessons from the past worth remembering: Larrey and triage. *Trauma*. 1999;1:86–89.
2. Sacco W, Navin M, Fiedler K, et al. Precise formulation and evidence-based application of resource-constrained triage. *Acad Emerg Med*. 2005;12:759–770.
3. Super G, Groth S, Cleary V. *START: A Training Triage Module*. Newport Beach, CA: Hoag Presbyterian Memorial Hospital; 1983–1984.
4. Garner A, Lee A, Harrison K, Schultz CH. Comparative analysis of multiple-casualty incident triage algorithms. *Ann Emerg Med*. 2001;38:541–548.
5. Benson M, Koenig KL, Schultz CH. Disaster triage: START, then SAVE–a new method of dynamic triage for victims of a catastrophic earthquake. *Prehospital Disaster Med*. 1996;11:117–124.
6. Nocera A, Garner A. An Australian mass casualty incident triage system for the future based on the mistakes of the past: the Homebush Triage Standard. *Aust N Z J Surg*. 1999;69:603–608.
7. Romig LE. Pediatric trauma. A system to JumpSTART your triage of young patients at MCIs. *JEMS*. 2002;27:52–58, 60–63.
8. Janousek JT, Jackson DE, Lorenzo RA, Coppola M. Mass casualty triage knowledge of military medical personnel. *Mil Med*. 1999;164:332–335.
9. Triage. In: Greaves I, Porter K, Ryan J, eds. *Trauma Care Manual*. Oxford, England: Oxford University Press; 2001.
10. Navin M, Waddell B. Triage is Broken. *EMS Magazine*. 2005;34(8):138–142.
11. Cone DC, MacMillan DS. Mass-casualty triage systems: a hint of science. *Acad Emerg Med*. 2005;12:739–741.
12. Gass S. Linear Programming. New York: McGraw-Hill; 1964.
13. Sacco W, Champion H, Henderson JW. Implementation of Severity Scores in Naval Casualty Care. Proc. Seventeenth Hawaii International Conference on System Sciences, 1984.
14. Sacco W, Champion H, Stega M. Computer Implementation of Severity Scores for Civilian Trauma Patient and Naval Combat Casualty Care. Proc. Proceedings of the 18th Hawaii International Conference on System Sciences, 1985.
15. Sacco W, Champion H, Stega M. Advances in Computerized Severity Scoring for Naval Combat Casualty Applications. Proceedings of the 19th Hawaii International Conference on System Sciences, Honolulu, 1986.
16. Harrell FE Jr, Lee KL, Mark DB. Tutorial in biostatistics: multivariate prognostic models: issues in developing models, evaluating assumptions, and adequacy, and measuring and reducing error. *Stat Med*. 1996;15:361–387.
17. Nathens AB, Rivara FP, Jurkovich GJ, Maier RV, Johansen JM, Thompson DC. Management of the injured patient: identification of research topics for systematic review using the Delphi technique. *J Trauma*. 2003;54:595–601.
18. Reading M, ed. *The Delphi Method: Techniques and Applications*. London: Addison-Wesley; 1975.
19. Navin M, Waddell B. A disaster doesn't have to be a disaster. An evidence-based triage method that takes the guesswork out of triage. *Eerg Med Serv*. 2005;34:71–75.
20. Champion HR, Sacco WJ, Copes WS, Gann DS, Gennarelli TA, Flanagan ME. A revision of the trauma score. *J Trauma*. 1989;29:623.
21. Baker SSP, O'Neill B, Haddon W Jr, Long WB. The Injury Severity Score: a method for describing patients with multiple injuries and evaluating emergency care. *J Trauma*. 1974;14:187–196.