5-1-1990

TraumAID: AI Support in the Management of Multiple Trauma

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Recommended Citation

Bonnie L. Webber, John R. Clarke, Ron Rymon, Michael Niv, and María Milagros Ibáñez, "TraumAID: AI Support in the Management of Multiple Trauma", . May 1990.

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-90-09.

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This paper outlines the particular demands that multiple trauma makes on systems designed to provide appropriate decision support, and the ways that these demands are currently being met in our system, TraumAID. The demands follow from: (1) the nature of trauma and the procedures used in its diagnosis, (2) the need to adjust diagnostic and therapeutic procedures to available resource levels, (3) the role of anatomy in trauma and the need for anatomical reasoning, (4) the role of non-specialists in managing trauma, and (5) the competing demands of multiple injuries and the consequent need for planning. We believe that these demands are not unique to multiple trauma, so that the paper may be of general interest to expert system research and development.

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MS-CIS-90-09
LINC LAB 163

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May 1990

A shorter version of this paper appears in the *AAAI Symposium on Artificial Intelligence and Medicine*, Stanford University, March 1990

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Abstract

This paper outlines the particular demands that multiple trauma makes on systems designed to provide appropriate decision support, and the ways that these demands are currently being met in our system, TraumAID. The demands follow from: (1) the nature of trauma and the procedures used in its diagnosis, (2) the need to adjust diagnostic and therapeutic procedures to available resource levels, (3) the role of anatomy in trauma and the need for anatomical reasoning, (4) the role of non-specialists in managing trauma, and (5) the competing demands of multiple injuries and the consequent need for planning. We believe that these demands are not unique to multiple trauma, so that the paper may be of general interest to expert system research and development.

1 Introduction

Injuries, accidental and intentional, result in more years of human life lost in the United States than any other disease [7]. According to Trunkey [12], deaths due to injury have a trimodal distribution. The first peak of deaths occurs immediately as a result of injury: such deaths are amenable to prevention. The second peak of deaths occurs within the first hours of injury: their number can be reduced by rapid delivery of expert care. The third peak is the result of late complications and is amenable to expert care before and after the development of complications. West [14] and others have clearly shown that 30 to 40% of trauma deaths within the first hours of injury can be prevented by *rapid* delivery of *expert* care.[1]

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[1] What proportion is due to the rapidity of that care and what, to its expertise has never been stated, but the perception is that both are involved.

Because of the need for rapid delivery of expert care, a major effort has been made to educate physicians so that they can provide an immediate expert response. This effort has been led by the American College of Surgeons through their Advanced Trauma Life Support (ATLS) course [2]. Its purpose is to enable physicians to provide immediate expert response in the initial evaluation, resuscitation, and stabilization of severely injured patients: The goal of our system, *TraumAID*, is to support their subsequent care during their *initial definitive management*, after resuscitation and stabilization.

TraumAID reflects a multi-year collaboration between the director of the regional trauma center at the Medical College of Pennsylvania (Clarke) and members of the Department of Computer and Information Science at the University of Pennsylvania. At the core of TraumAID is a rule-based expert system. Its knowledge base has been developed as a series of inter-connected modules, covering penetrating injuries to the abdomen and penetrating injuries to the chest, with current work on a module for injuries to the upper extremities. Extensions to TraumAID are planned for blunt injuries to the abdomen and chest, and then for injuries to the lower extremities, head, neck and perineum.

This paper is oriented towards the particular demands that multiple trauma makes on systems designed to provide support for its diagnosis and treatment and how these demands are being met (or are planned to be met) in TraumAID. These demands follow from: (1) the nature of trauma and the procedures used in diagnosis, (2) the need to adjust procedures to available resource levels, (3) the role of anatomy and the need for anatomical reasoning, (4) the role of non-specialists in managing trauma, and (5) the competing demands of multiple injuries and the consequent need for planning. Each of these topics is discussed briefly, with a focus on *planning*, since it is here that we have recently moved from an *ad hoc* to a more theoretically motivated approach.

2 Cycles of Reasoning and Action

Here we have grouped together three features of multiple trauma and its diagnosis that motivate a basic cycle of diagnostic reasoning on the part of the system, followed by action on the part of the physician. They are all reasons for not terminating diagnostic reasoning with the identification of a treatable diagnosis and recommendation of an appropriate treatment:

1. Therapeutic procedures can themselves provide further diagnostic information. For example, a chest tube inserted to treat a hemothorax can, if bleeding persists, provide evidence that the patient is suffering a massive hemothorax. This in turn requires a thoracotomy as its appropriate treatment.

2. Injuries may lead to complications. Thus identifying a treatable injury may suggest not only necessary therapy but also other possible injuries that require separate treatment. For example, injury to the thoracic aorta can in turn cause injury to the spinal cord by reducing its blood supply. Thus concluding the former should trigger suspecting the latter, leading to requests for the information needed to conclude the latter or to rule it out.
3. In trauma, it is not uncommon for patients to present with multiple injuries. At the same point at which the system has enough information to make one treatable diagnosis (and recommend an appropriate therapy), it may still be recommending diagnostic procedures to identify other injuries.

TraumAID copes with all three features through cycles of reasoning and action. During reasoning, its basic pattern of operation is as follows: Starting from an initial description of a patient's wounds and any initial findings that the physician may report, it performs *forward reasoning* to diagnostic suspicions and conclusions, followed by *backward reasoning* to identify information that would allow those suspicions to be confirmed or eliminated. Information not already available is requested from the physician.

Both acquiring information and treating already concluded diagnoses requires actions on the part of the physician. Whatever information is acquired and procedures are performed are reported to the system, which then triggers another instantiation of its basic pattern. This cycle of reasoning and action also captures a primitive form of temporal succession through which the system can distinguish a *request* for a procedure from its subsequent *performance*, the *first* performance of an action from its *second* performance, etc.

3 Adjustment to Resource Levels

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The need to adjust reasoning and action in multiple trauma to different resource levels is motivated by the fact there is often no choice as to where acutely injured patients are managed. The closest site may be a Level I Trauma Center, or it may be a rural hospital. One would like to avoid having to write a whole new set of rules for each environment. Our current solution stems from a request from the Navy to develop a version of TraumAID for use by independent-duty medical corpsmen on submarines [5]. Instead of creating a new rule base, we modified the version of the system designed for use by physicians in a well-equipped Trauma Center. The modifications retain the same rule base but accommodate the absence of particular diagnostic tools (e.g., computerized tomography) through a set of *safe assumptions* represented as default values. These are used if the actual result of a finding cannot be determined because of a lack of equipment or training. Conclusions reached in this way are identified as such.

For example, TraumAID will suspect bladder injury in cases where a patient has sustained a wound in his lower abdomen and shows signs of hematuria. Conclusive evidence would come with a cystogram. However, this test is unavailable to submarine corpsmen, so TraumAID makes a safe assumption – in this case, to act as if the result were *positive* – which leads it to recommend that the patient be evacuated urgently to have the bladder repaired with chromic sutures and drainage.

To accommodate the corpsmen's setting and skills, TraumAID's therapeutic recommendations were systematically translated to ones appropriate for the corpsmen, most often involving observation or evacuation. After this systematic translation, it was only necessary to hand-modify one set rules (9 in all) dealing with the diagnosis of hemopneumothoraces, in order for the system to conform to its new environment. These modifications all involved a test so fundamental – a chest x-ray – that no standard default was possible. Instead, another test (auscultation of the lungs) was substituted which, although less reliable, can be performed by a corpsman in an environment that lacks x-ray resources.

We have yet to consider the problem of resource adjustment in more generality, but it is clearly a useful direction in which expert systems can develop.

4 Anatomical Reasoning

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There are several types of anatomical reasoning that take part in the diagnosis and treatment of multiple trauma. Here we identify them and how they are currently supported in TraumAID.

Reasoning based on Wound Location. Wound location can be used to suggest the type of injury a patient has sustained. Currently in TraumAID, the body surface is segmented into labelled regions. The segmentation is such that a wound to a particular labelled region will suggest particular injuries. For example, one labelled region is the *midline posterior chest.* A wound to this region leads directly to a suspicion of *spinal cord injury.*

Reasoning based on Wound Direction. If one knows both the location and direction of a penetrating wound, one can reason about which organs may be along the path of penetration and thus may have been injured. (Conversely, one can eliminate suspicions about direct injuries to organs not along this path.) Such suspicions can be more accurate than those based on wound location alone. TraumAID currently performs this type of anatomical reasoning purely through its forward-chaining *suspect rules*. However, given its importance, we have begun to develop a octree model [4, 13] of the chest and abdomen that will eventually mediate wound specifications made through TraumAID's Hypercard interface[2] to its rule-based expert system. Suspected injuries derived from the model will then trigger attempts to draw conclusions about these injuries, much as suspicions derived from its *suspect rules* do in the current system.

Part-Whole Reasoning. As in [8], one wants to use anatomical part-whole relations to make statements at the highest possible level of generality. TraumAID currently makes use of two separate abstraction mechanisms. One is accessible to the pattern matcher used in rule application so that, for example, an argument of WOUND-LOCATION = 'chest will match any value of WOUND-LOCATION that is a subpart of chest. The other makes use of TraumAID's forward-chaining *conclude rules* so that, for example, one does not have to separately specify each possible chest wound that might lead to an aortic injury. The latter mechanism is used when both the more general and the more specific information is relevant, the former, when only the more general is (but more specific information has been provided).

Reasoning about Connectivity. As in [3], the diagnosis of multiple trauma must take nervous system connectivity into account in interpreting findings, so that, for example, if a patient presents with two penetrating wounds, each of which may have injured his spinal cord, the system does not draw the same conclusion it would if only one wound were present (other findings being equal). One must also consider circulatory system connectivity in interpreting findings, since the absence of a bullet in an expected location may not mean that it has exited the body: it just may have been transported elsewhere by blood flow. Neither of these types of reasoning about connectivity is done in the current version of the system.

5 TraumAID: Critique Mode Interaction

Traumatic injury may be sustained at any time of the day or night and may injure any organ Although Emergency Room personnel are all medical practitioners, a particular patient's injuries may demand the expertise of a specialist who is not available. With multiple trauma this problem grows in both urgency and complexity.

To allow TraumAID to be used as a backup consultative tool for ER physicians faced with injuries outside the spheres of their expertise, we have been developing an alternative mode of interaction to that described in the Introduction. This we call *critique mode interaction*. Here the physician provides not only findings but also his/her proposed diagnoses and proposed plan of action.

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[2] currently being developed by Ashesh Shah, a computer science undergraduate at Penn

The system can then critique this plan with respect to its own, pointing out significant deviations and proposing alternative solutions where appropriate. As such, critiquing mode can also serve as an educational tool when used off-line on test cases.

A plan in TraumAID consists of a set of diagnostic and therapeutic procedures, the former being driven by suspicions and the latter being grouped around the diagnosis that requires them. The elements of a plan that TraumAID should address in critique-mode are: (1)diagnoses reached by the physician; (2) procedures that s/he considers necessary to reach those diagnoses; and (3) the therapeutic procedures suggested to treat the patient.

Currently, TraumAID's critique mode can accept the diagnosis and treatment procedures of the physician's plan (goals 1 and 3), and build a critique text for any possible combination of correct and incorrect elements in the plan. This plan is input through a sequence of pop-up menus, to reduce the amount of typing necessary.

5.1 Critique Features

We shall illustrate the features of TraumAID's critique mode through the following example.

> An adult male presents with a single stab wound in the midline lumbar posterior torso (mid lower back). He is not in shock and has lost motor control in his right leg as well as sensation in his left leg. The system concludes spinal cord injury and suspects abdominal wall injury. There is as yet insufficient evidence to disprove or conclude the latter.

Correct partial plan. For a given diagnosis, if both the diagnosis and its associated therapeutic procedures are part of the system's plan, the system responds with approval.

Physician's plan:

> **Diagnosis** – Spinal Cord Injury
>
> **Treatments** – Inmobilize the patient, Neurosurgical Consultation, Paraplegia Rehabilitation.

System's response:

> There is enough evidence to conclude what you suggested: Spinal Cord Injury. Inmobilize the patient, Neurosurgical Consultation and Paraplegia Rehabilitation are, as you mentioned, the correct protocol.

Missing diagnosis. When a concludable diagnosis is missing from a physician's plan[3], TraumAID reports the relevant evidence, together with the role it plays in deriving the diagnosis. For teaching purposes, TraumAID also provides the set of therapeutic procedures that address that diagnosis.

System's response (in the case where physician's plan does not include Spinal Cord Injury):

> Based on the evidence:
>
> ** Wound in the Midline Posterior
>
> ** Loss sensation on the left leg
>
> ** Loss motor on the right leg
>
> ** Insufficient evidence to conclude Ischemic Spinal Cord Injury[4]
>
> it can be concluded that the patient has Spinal Cord Injury. The standard protocol is: Immobilize the patient, Neurosurgical Consultation, Paraplegia Rehabilitation.

Difference in therapeutic procedures. Here, the physician's therapeutic procedures for a given diagnosis do not agree with those of the system. The system in this case confirms the therapeutic procedures it concurs with and warns about those that it does not. In the first examlpe, there are no procedures on which physician and system concur. In the second, there is a single procedure that the system disagrees with.

Physician's plan:

> **Diagnosis** – Spinal Cord Injury
>
> **Treatments** – Minimal Fluids, Cover Wound Occlusive Dressing.

System's response:

> You have reached the diagnosis Spinal Cord Injury that matches the conclusion that the system has reached, but none of the treatments that you included in your plan, Minimal Fluids and Cover Wound Occlusive Dressing, agrees with the standard protocol. The standard protocol is: Inmobilize the patient, Neurosurgical Consultation and Paraplegia Rehabilitation.

Physician's plan:

> **Diagnosis** – Spinal Cord Injury

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[3] Dr Clarke reports that it is not uncommon for diagnostic tests to be ordered for a diagnosis evident from the data already collected from the patient, incurring extra costs and wasting valuable time

[4] Ischemic Spinal Cord Injury is another cause of paralysis.

Treatments – Inmobilize the patient, Neurosurgical Consultation Paraplegia Rehabilitation and Minimal Fluids.

System's response:

> You have correctly diagnosed Spinal Cord Injury and suggested Inmobilize the patient, Neurosurgical Consultation and Paraplegia Rehabilitation. However, there is no need to treat the patient with Minimal Fluids.

Insufficient evidence for a diagnosis. Recall from Section 2 that a diagnosis may either be suspected or concluded. If the physician concludes a diagnosis that the system still only suspects (because of insufficient evidence), TraumAID suggests the physician enter its regular 'let the system ask' mode that will allow it to ask for the pieces of evidence that it needs to either conclude or rule out that diagnosis.

Physician's plan:

Diagnosis – Abdominal Wall Injury

Treatments – Cover Wound Occlusive Dressing

System's response:

> Although there is some evidence to suspect Abdominal Wall Injury:
>
> ** Wound of type stab in the abdomen
>
> ** There is no enough evidence to conclude Non Specific Intra Abdominal Injury
>
> nothing can be concluded without more evidence. To further investigate this diagnosis, please select 'let the system ask' command.

Note that Non Specific Intra Abdominal Wall Injury is another, more serious injury.

A diagnosis known to be false. If the physician includes in his/her plan a diagnosis that the system has concluded to be false, an appropiate comment is made to the physician. However TraumAID can not determine, on the basis of what it knows, why the physician reached the false conclusion, so it does not attempt to further correct the cause of the physician's error.

Physician's plan:

Diagnosis – Compound Fracture Vertebra

Treatments – Neurosurgical Consultation, Inmobilize the patient and Minimal Fluids.

System's response:

> The system has reached the conclusion that the patient does not have Compound Fracture Vertebra, because some conditions needed for that conclusion do not hold.

Unmotivated diagnosis. If a diagnosis in the physician's plan is neither suspected nor concluded by the system, again the physician is informed, but is also invited to provide more information so that the system can form an opinion as well.

Physician's plan:

> **Diagnosis** – Ischemic Spinal Cord Injury
>
> **Treatments** – Thoracic Aorta Repair with Shunt, Paraplegia Rehabilitation.

System's response:

> There is no enough evidence to either suspect or make any conclusion about Ischemic Spinal Cord Injury. To investigate Ischemic Spinal Cord Injury, please provide more information.

5.2 Future Developments

We are planning several improvements to TraumAID's critique mode interaction. Most importantly, it must be extended to critique diagnostic procedures in the physician's plan which the system may find either unmotivated, in conflict with other procedures included in the plan, slower or more expensive than another one that provides essentially the same information, or unavailable at that institution. In the latter cases, an alternative procedure should be recommended.

Secondly, TraumAID should record dissenting opinions: we are aware that diagnostic criteria can depend on the human expert providing the system's medical knowledge (in our case Dr. John Clarke) and are therefore subject to disagreement. Because of this, the system should be extended to record opinions from physicians when these physicians do not agree with the conclusion reached by the system. Such free-text comments will periodically be examined and will help extend the knowledge according to other experts' experience.

Thirdly, the system should optionally provide additional text that can clarify why a particular fact is important in the context of the different possible diagnosis the fact participates. While such texts would most likely be "canned" (rather than generated automatically), it will undoubtly be very useful for educational applications of this critique-mode interaction.

6 Planning

One of the major problems we have had to address in developing TraumAID is the fact that it is not uncommon for patients to present with multiple problems: some may be linked to the same injury, others may result from distinct injuries. Each problem on its own demands a sequence of diagnostic and therapeutic actions, which the physician in charge must follow. Taken together, they present a major problem of what to do and when. What is unique to the problem of planning a course of diagnostic and therapeutic procedures is that the final therapeutic goals are never entirely known when the planning process begins. In fact, it is the *goal* of diagnostic procedures to identify, directly or indirectly, therapeutic goals that the plan must then address. Planning in this context requires that plans constantly be reassessed, much as in reactive planning [1, 6, 11].

The role of planning in TraumAID is to coordinate into a plan the diagnostic and therapeutic recommendations made by the expert system and to revise that plan as new suspicions and conclusions develop. Planning is performed by an independent module. Control of the augmented system alternates between expert system and planner, with the former re-invoked, as before, when the physician reports the results or the performance of actions. This is done until surgery is determined to be unnecessary or the patient is taken to the Operating Room or Trauma Unit, which concludes the phase of *Initial Definitive Management.* While the planner is both motivated and described in more detail elsewhere [10], there is space here for a brief overview.

In the augmented system, the expert system presents the planner with a set of management goals to fulfill. (These may of course change over the course of plan execution.) In response, the planner must find a partially ordered set of procedures that satisfy these goals. To do this, it uses a knowledge base describing the relationship between *management goals* and the *procedures* that address them.

Each management goal is accompanied by a priority indicator that classifies it into one of six classes: airways, circulation, neurologic, contamination, orthopedic stability and other. This priority will be inherited by the chosen procedure and used in scheduling it.

Procedures are ordered sets of actions, which may be primitive actions or management goals. Without loss of generality, we allow only two types of procedures: (1) *declarative* procedures and (2) *action* procedures. A declarative procedure consists of only management goals and serves essentially for representing a hierarchy of management goals. An action procedure consists of only primitive actions. To allow reasoning about procedure compatibility, actions carry their preconditions, contra-indicators, ramifications, possible side effects[5],

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[5] Side effects are suspected (in a sense that is compatible with suspicion in the rule-based

risk and accuracy, cost and resource requirements.

Because each management goal can be satisfied by several different procedures, we use an algorithm similar to Reiter's [9] to find a set of procedures that covers the set of management goals.[6] We cover first goals with higher priority and proceed along the list of management goals.

A plan is constructed recursively, via a three-phase process. There is an initial phase in which a coarse ordering of the recommended procedures is produced based on standard practices of trauma care and logistics, a second phase in which conflicts between procedures are identified and resolved, and a third phase in which optimization is done locally on the initial steps of the plan.

Standard practices of trauma care call for attention to management goals involving the patient's airway, then to their circulation (treating bleeding and impairments to the movement of blood), then to their neurological stability, then to eliminating contamination, then to orthopedic stability and only then to other types of injuries. There is also a (partial) *logistic ordering* in which procedures done in the Emergency Room (**ER**) are done before procedures in the Radiology Department (**XR**) which precede procedures done in either the Operating Room (**OR**) or Trauma Unit (**TU**). To impose a coarse ordering on the recommended procedures, they are sorted into bins with the ordering (**ER**, **XR**, **OR** or **TU**) as the major sort key[7] and standard practices of trauma care as the minor sort key.

Following this coarse sorting, pairwise conflicts are identified and resolved. There are two types of conflicts: priority conflicts between the demands of logistic ordering and standard practices, and within-bin conflicts, which are conflicts between procedures with the same priority. The former appear to be very rare, and can be resolved simply on the basis of whether the patient is stable or not.[8] If the patient is not stable, standard practices take precedence. If he is stable, then logistics take precedence since ER and X-Ray procedures are generally not costly in terms of time.

Conflicts between procedures with the same priority, taken care of at the same site, are more common. In some cases, the conflict is only partial: one ordering of the procedures is ruled out on the basis of conflicting ramifications, side effects or contra indicators. In this case, conflict resolution merely involves choosing a possible ordering. In other cases, the conflict is complete: no ordering is possible. In this case, the planner will try to either (1) replace one procedure with another that satisfies the same goals but is not in conflict or (2) replace

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system) as opposed to ramifications that are concluded upon the completion of the action.

[6] Reiter uses his algorithm for diagnosis, to find a set of faulty components that account for the malfunctions of a system

[7] In Clarke's experience, it is rare that a patient must be transferred from OR back to XR or ER, or from XR to ER during initial definitive management.

[8] This is again based on Clarke's extensive experience.

both procedures with a third that satisfies the goals of both. This process of conflict resolution demands a rich knowledge of procedures, including knowledge of their preconditions, contra indications, ramifications, the goals they are able to satisfy, and their cost, risk and accuracy. If the planner cannot achieve resolution in one of these two ways, as a matter of practicality resolution would be left to the physician.

The third stage of planning involves local optimization. Optimization is only done pairwise, on the first steps of the proposed plan, since later steps of the plan may be eliminated by the acquisition of new knowledge or as a result of complications while executing earlier steps. Optimization may involve partial merging of procedures that share subparts, substitution of one procedure with another one which can then undergo partial merging, or substitution of a set of procedures with a single one that satisfies the set of their goals. For example, if the first steps of a proposed plan consist of lavage and arteriogram, CAT scan might be substituted for lavage, to take advantage of the injection of dye required for the arteriogram. Such optimization also demands a rich knowledge of procedures, including knowledge of their component actions, the goals they satisfy, and their cost, risk and accuracy. Any optimizations produced by the planner are presented with an explanation identifying the originally recommended procedures and the type of optimization performed.

7 Conclusion

In this short paper, we hope to have shown the demands that multiple trauma places on systems designed to support its diagnosis and treatment. These demands are likely not unique to multiple trauma, so that we hope this discussion of issues and our solutions (both current and proposed) may be of benefit to other researchers as well.

ACKNOWLEDGMENTS

This research was supported in part by the Office of Naval Research under subcontract Grant N00129-89-C-0006. The authors thank Maria Ibanez, Len Karpf and Charlie Ortiz for their comments on earlier versions of the paper.

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