Modelling Trauma Physiology for Large Crisis Management

Alessandro Borri[(a)], Christos Dimopoulos[(b)], Simona Panunzi[(a)], Rachele Brancaleoni[(c)],

Claudio Roberto Gaz[(1),] Daniele Gui[(c)], Sabina Magalini[(c)], Andrea De Gaetano[(a)]

[(a)]CNR-IASI Biomathematics Laboratory, Rome, Italy
[(b)]Department of Computer Science & Engineering, European University Cyprus, Cyprus
[(c)]Catholic University of the Sacred Heart, Rome, Italy

[(a)]{alessandro.borri,simona.panunzi,claudior.gaz,andrea.degaetano}@biomatematica.it
[(b)]c.dimopoulos@euc.ac.cy
[(c)]rachele.brancaleoni@gmail.com,{daniele.gui,sabina.magalini}@rm.unicatt.it

ABSTRACT

In recent years, there has been a rise in Major Incidents with big impact on the citizens health and the society. Without the possibility of conducting live experiments when it comes to physical trauma, only an accurate in-silico reconstruction allows us to identify organizational solutions with the best possible chance of success, in correlation with the limitations on available resources (e.g. medical team, first responders, treatments, transports, and hospitals availability) and with the variability of the characteristic of event (e.g. type of incident, severity of the event and type of lesions).

Utilizing modelling and simulation techniques, a simplified mathematical model of physiological evolution for patients involved in physical trauma incident scenarios has been developed and implemented. The model formalizes the dynamics, operating standards and practices of medical response and the main emergency service in the chain of emergency management during a Major Incident.

Keywords: predictive models for adverse outcomes; personalized patient treatment; health monitoring applications

1. INTRODUCTION

It is today clear that the occurrence of Major Incidents (MIs) – situations where available resources are insufficient for the immediate need of medical care – has increased significantly parallel to the technical and economic development in the world (Lennquist S., et al., 2012). The World Disaster Report 2007 showed a 60% increase in the occurrence of incidents defined as major during the decade 1997-2006 (Klyman, Y., Kouppari, N., Mukhier, M., 2007). During the last decade, the reported deaths from such incidents increased from 600,000 to more than 1,200,000 and the number of affected people increased from 230 to 270 million (Klyman, Y., Kouppari, N., Mukhier, M., 2007). MIs have previously been considered as low probability events that might inflict bodily harm, incapacitation, or even fatalities, and generally have a big impact on the citizens and the society (Smith, E., Waisak, J., Archer, F., 2009). The main causes of this increase have been recognized in (Frykberg, E.R., 2002): the increase of global population; the escalation of natural disasters, due to global warming and climate change' ; the significant amounts of flammable, explosive, chemical, and toxic agents which are produced, transported on roads and railroads, and used every year; the global terrorism (e.g., chemical warfare agents (CWA), biological warfare agents (BWA), and radiological and nuclear particulate hazards); the continuing urbanization, which has resulted in an increasing number of people living or gathering together for public events in crowded areas. Such areas are also potential targets for terrorist attacks or constitute a risk in themselves, because, it can be difficult and time-consuming to evacuate a large number of people from physically constrained areas (e.g., in case of structural collapse or fire).

Parallel to the significant increase of MIs, the vulnerability of our health care system to such situations has increased: increasing demands on efficiency reduce or eliminate the "resilience capacity" for high loads of casualties (Lennquist S., et al., 2012).

The goal of the health care system during the occurrence of an MI is to reduce or eliminate loss of life and health, and subsequent physical and psychological suffering (Lennquist, S., 2003a).

The achievement of such a goal requires two actions (Lennquist, S., 2003a):

1) Relocation of available resources to where they are most needed, and rapid mobilization of additional resources (personnel and materials);
2) Optimal utilization of available resources through accurate priorities between patients

and measures and through the use of simplified methods for triage, treatment and transport (Lennquist, S., 2003b).

Relocation and mobilization of resources can be enhanced through the introduction and proliferation of good and accurate mathematical models to manage incident medical response (Walter F., Dedolph R., Kallsen G., et al., 1992), for example to simulate physiological value, predict adverse outcomes and personalize the treatment of the patients.

Advanced simulation models can illustrate all components in the chain of MI management (e.g., patient evolution, triage, treatment, transport, and hospital) and aim at developing and ensuring resilience capacity. The improvement of resilience and the better integration of health care systems in real operations will enhance the safety and security of citizens.

2. METHODS

Utilizing modelling and simulation techniques, we have developed and implemented a mathematical model for the physiological patient evolution during/after physical trauma. The assessment of the peculiarities of the patient response of individual patients to medical intervention by mathematical and computer modelling techniques is a quite recent approach (O. Bouamra, M.M. Lesko, 2014), which underwent a dramatic development over the past few years (M. Hill, 2010), due to the technological progress allowing widely available computing power.

From the mathematical point of view, the patient condition is described in terms of continuous physiological variables, and the state of the system can assume infinitely many values. As illustrated hereafter, the evolution is governed by systems of Ordinary Differential Equations (ODEs) which determine the “trajectory” of the physiological (state) variables.

2.1. Taxonomy

For the implementation of a mathematical model of physiological patient evolution during a MI, the following taxonomy has been used, which involves the following classes:

- Events: an event is an accident or an incident that involves a certain amount of people. We have built an Event Library, which contains physical trauma incidents (Frykberg, E.R. 2002, Bertazzi, PA, 1989, Kales, S.N., et al., 1996, Nutbeam, T., Boylan, M., 2013):
    - motorway accident;
    - bridge collapse;
    - ship explosion;
    - train crash;
    - stadium crush;
- Lesions: a lesion is a damage or an injury that can afflict in general all the systems of the human organism. An event is liaised to a set of lesions with a conditional probability of occurrence. A Lesions Library has been built, containing physical lesions (Alywin, C.J., 2006, Moreira, L.B., et al., 1999, Binder, S., Bonzo, S., 1989, Burgess, J.L., et al, 1997, Ellis, D., Hooper, M., 2010, Greaves, I., Porter, K., 2007):
    - head trauma;
    - facial trauma;
    - chest trauma;
    - spinal trauma;
    - abdominal trauma;
    - pelvic trauma;
    - extremity trauma.
- Physiology: in agreement with the ABCDE Primary Survey and Resuscitation (Alywin, C.J., 2006), there are only five main ways to die, from fatal complication involving:
    - Airway (A);
    - Breathing (B);
    - Circulation (C);
    - Disability Nervous System (D);
    - Extra Damage or Exposure with Environmental Control (E).

  Accordingly, the patient dynamics can be described by a set of physiological variables, based on ABCDE paradigm. The set of physiological variables consists of 10 variables:
    - A1 (i.e., intact, at risk, partially obstructed, or completely obstructed airway);
    - B1 (i.e., respiratory rate);
    - B2 (i.e., tidal volume);
    - B3 (i.e., oxygen saturation, SpO2);
    - C1 (i.e., heart rate);
    - C2 (i.e., Mean Arterial Pressure, MAP);
    - D1 (i.e., Glasgow Coma Scale, GCS);
    - D2 (i.e., seizures);
    - D3 (i.e., cholinergic activity);
    - E1 (i.e., trauma, burns, and contamination).
- State Variables: the patient dynamics is described by:
    - $x(t)$, which is the current state of each variable;
    - $v(t)$ (i.e. $dx(t)/dt$), which is the speed at which each variable changes its state.
- Therapeutic maneuvers: there is a set of therapies (according to the ABCDE treatment) repairing the damage that afflicts the physiological variables. We have built a Therapeutic Maneuvers Library, which contains (Nutbeam, T., Boylan, M., 2013,

Wyatt, J.P., et al., 2012, Waldmann, C., Soni, N., Rhodes, A., 2008, Singer, M., Webb, A.R., 2009, Cone, D.C., Koenig, K.L., 2005):

- decontamination;
- oxygen;
- intubation;
- ambu-bag;
- Hyperbaric Oxygen Therapy (HBOT);
- saline;
- blood;
- vascular surgery;
- neural surgery;
- orthopedic surgery;
- tourniquet;
- respiratory drugs (e.g., bronchodilators, respiratory stimulants);
- cardio drugs (e.g., β-adrenergic agonist as adrenaline, chronotropes as atropine);
- neuro drugs (e.g., anticonvulsant drugs as benzodiazepines).

- Lesions/Maneuvers delta-alpha matrices: each lesion affects one or more physiological variables with a maximal initial damage (delta$^-$) and a maximal worsening rate per unit time (alpha$^-$); symmetrically, each therapeutic maneuver repairs one or more physiological variables with a maximal initial improvement (delta$^+$) and a maximal improvement rate per unit time (alpha$^+$). Tables 1 and 2 contain some parameter values for delta and alpha for a subset of lesions and maneuvers.

- Assets: an asset is characterized by a collection of therapeutic maneuvers. An Assets Library has been built, which contains:

  - ambulance;
  - emergency room;
  - decontamination team;
  - operating theatre;
  - police car;
  - on the scene (i.e., the absence of therapies).

The assets link the patient model to a future logistic model, which takes into account the real-time availability of the resources.

2.2. Mathematical Model

The mathematical model describes the physiological patient evolution in terms of piecewise-linear trajectories in the state space, where the patient dynamics is described by means of normalized physiological values (see previous section for more details). In the normal form of first order, the evolution of each variable satisfies the following differential equation:

$$\frac{dx(t)}{dt} = -\alpha + u(t) \qquad t \geq t_0 \qquad (1)$$

starting from the initial condition:

$$x(t_0) = 1 - \Delta \qquad (2)$$

where:

- t_0 is the start of the event;
- x(t) is the value assumed by each physiological variable at time $t \geq t_0$, when the damage of each variable starts. Each variable takes values in [0,1], where 1 is the initial healthy value, and has a lower-bound value under which the patient's health is compromised;
- $x(t_0)$ is the value assumed by each physiological variable at time $t = t_0$;
- $dx(t)/dt = v(t)$ is the speed at which each variable changes its state;
- Δ: $\Delta \in [0,1]$ is the maximal initial damage at time t_0;
- α: $\alpha \in \mathbb{R}_0^+$ is the maximal worsening rate [relative damage/unit time];
- u(t) is a non-negative therapy component. Symmetrically to what happens for lesions, it provides instantaneous improvements Δ [relative damage] and positive healing rates α [relative damage/unit time] for some therapies and some physiological variables.

However, the event starts affecting the patient's status at (possibly) different times for each individual, causing lesions, namely reductions in the value of one or more physiological variables.

	B1 Delta	B1 Alpha	….	C2 Delta	C2 Alpha	….	E Delta	E Alpha
Head/Neck	-0.3	-1.2	….	0	-0.6	….	-0.1	-0.3
Face	-0.2	-1.2	….	0	-0.6	….	-0.1	-0.3
Chest	-0.9	-0.6	….	-0.9	-1.2	….	-0.1	-0.3
Abdomen	-0.2	0	….	-0.9	-1.2	….	-0.1	-0.3
Extremities	0	0	….	-0.5	-1.2	….	-0.1	-0.3
External	0	0	….	-0.4	-0.6	….	-0.9	-0.6

Table 1: Effects of some lesions on the physiological variables in terms of instantaneous maximum damage (in fraction) and maximum rate of worsening (in fraction/hour)

	B1 Delta	B1 Alpha	….	C2 Delta	C2 Alpha	….	E Delta	E Alpha
Oxygen	0	0.06	….	0	0	….	0	0
Intubation	1	60	….	0	0	….	0	0
Ambu bag	0.5	30	….	0	0	….	0	0
Saline infusion	0	0	….	0.2	6	….	0.2	3
Blood infusion	0	0	….	0.4	6	….	0.1	3
….	….	….	….	….	….	….	….	….

Table 2: Effects of some therapies on the physiological variables in terms of instantaneous modifications (in fraction) and of variation of the rate of change (in fraction/hour)

3. IMPLEMENTATION

To run simulations, the following functions have been preliminarily implemented in Matlab and then made available as webservices:

- GeneratePatients: this function randomly generates patients, affected by different lesions. The degree of severity of each patient can be sampled according to different (choosable) distributions: gaussian, uniform or triangular;
- EvolvePatients: this function simulates the patients evolution from (1)-(2), with and without therapeutic maneuvers;
- TimeToDeath: this function calculates the time to death for each patient, if there is not a medical treatment with therapeutic maneuvers;
- TriagePatients: this function simulates a patients triage, based on the time to death, and gives the color code according to literature review (Jenkins, J.L., et al., 2008, Partridge, R.A., et al., 2012).

The architecture follows a simple client-server paradigm: the models have been implemented by means of web-services, running on a LAMP (Linux-Apache-MySQL-Php) server running on a workstation in the CNR-IASI Biomathematics Laboratory, located in the Gemelli Hospital in Rome, Italy.

The syntax and the input-output description of each service, in terms of number and type of input-output parameters, is contained in the Web Services Description Language (WSDL), publicly available at the web address http://biomat1.iasi.cnr.it/webservices/master/webservice.wsdl. An example of Java Client calling some of the functionalities offered by the web-service is illustrated in Fig.2.

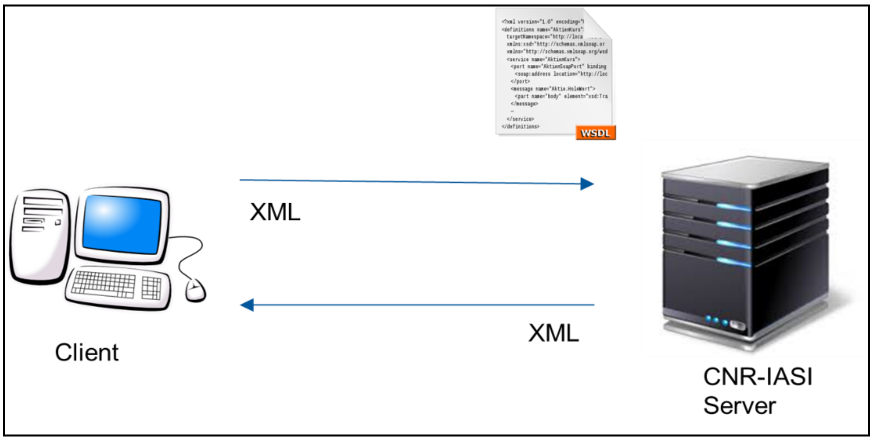

Figure 1: Scheme of the architecture used for the modeling web-services

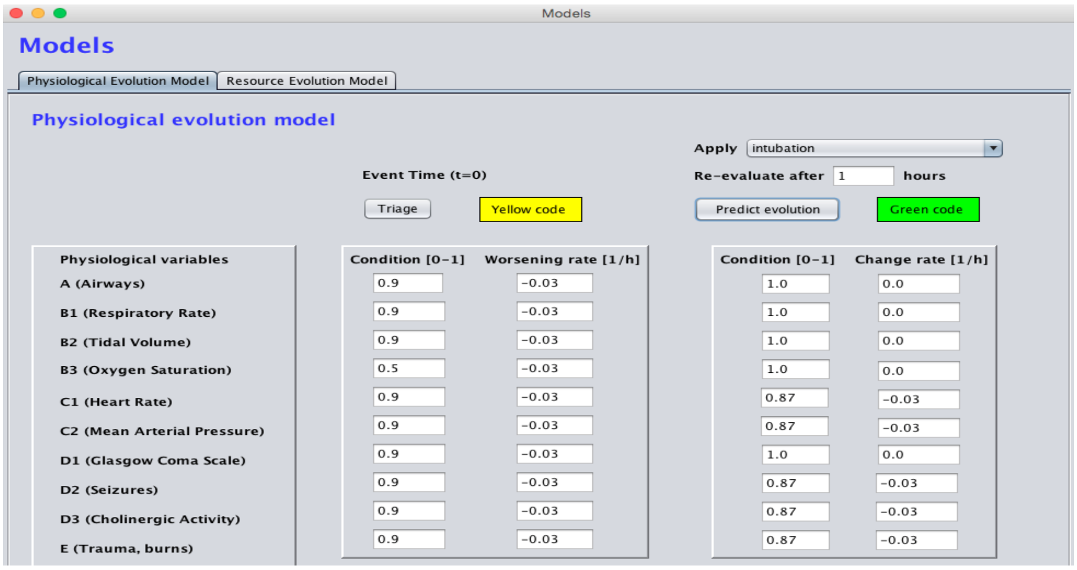

Figure 2: A Java client calling the mathematical model, involving also the TriagePatients functionality

4. DISCUSSION

We have developed and implemented a mathematical model of the physiological patient evolution during/after physical trauma events. The evolution of the value of 10 physiological variables (i.e., A1, B1, B2, B3, C1, C2, D1, D2, D3, and E1) is simulated in different physical trauma incident scenarios; the ultimate goal is to predict adverse outcomes with simplified methods for triage and personalize the treatment of the patients with available therapeutic maneuvers.

The results could provide a benchmark for potential introduction and proliferation of applications to be employed in real operation during MIs medical response, with potential improvements on the safety and security of citizens. In particular, it will allow the development of health monitoring applications aiming at: saving data remotely; producing reports on the health status of each patient; supporting decision-making during MIs, where medical staff act in limited time, under pressure, without having a second decision-making chance, outside their own medical specialties, and with high load of casualties.

The future perspective is to link this physiological patient-evolution model to a logistic model in order to: handle/request stockpiles and available resources during emergency; plan them in the preparedness phase for particular events, as mass gatherings; analyze old and new vulnerabilities (e.g., the overpopulation and how this effects healthcare) to enhance the resilience capacity and the better integration of healthcare systems. These models will be implemented in telemedicine tools to insure an interoperability standardization for medical response during MIs. Such tools could be used also during interactive training by emergency medical practitioners (which cannot be trained in real situations as MI) in order to "learn by doing".

ACKNOWLEDGMENTS

The research leading to these results has been partially supported by the EU-funded research projects EDEN, PULSE, IMPRESS under the European Union Seventh Framework Programme for Research [FP7/2007-2013].

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